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# COMPOSITES BASED ON METALLIC FOAMS: PHENOMENOLOGY; PRODUCTION; PROPERTIES AND PRINCIPLES

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**Abstract** – Since their re-discovery by the scientific world at the beginning of the last decade, closed cell metal foams for structural applications have found their way into series production. However, most of today's real world applications do not rely solely on the porous metal. In contrast, the components in question tend to combine the foam with various other materials such as conventional metals, ceramics or polymers. The present study gives an account of the variety of such material combinations based on FOAMINAL® metal foams produced according to the powder compact melting or Fraunhofer Process.

The numerous types and classes of such materials as defined by the nature of components are presented. Currently available manufacturing routes are discussed in terms of individual process steps, geometries achievable, estimates of relative component costs etc.

Light is shed on the properties of such materials, and the way they are influenced by the selection of individual components is investigated for simple geometries and load cases. For these, principles are identified which govern the optimal choice of components. Applications which have already entered series production or have been investigated in the course of feasibility studies are analysed in view of these principles.

**Keywords:** aluminium, foam, compound

## 1. INTRODUCTION

Metallic foams have been subject to investigation for more than 10 years. Characteristic properties like e.g. low density, high weight specific stiffness, extraordinary energy absorption, remarkable vibration attenuation and high fire resistance have been identified. Especially the high energy absorption efficiency independent of the loading direction fuelled the interest from automotive industry. It has been shown that with increasing porosity most properties, including strength, stiffness and conductivity, decrease exponentially [1]. Based on the identified unique properties many feasibility studies were performed and prototype parts have been produced for a broad variety of applications. It is understood that simply replacing a material by another in an existing structure will in most cases not lead to an improved overall performance. For metallic foams, it is furthermore agreed that the material's unique properties can best be used in composite structures where two or more characteristic foam properties are employed and where high tensile loads are sustained by conventional, dense materials [2].

## 2. METAL FOAMS

Closed cell metallic foams can be produced according to various procedures [3]. Two main process routes have been established. One process route is based on injection of gas into a liquid metal through nozzles or via decomposition of a homogeneously distributed foaming agent. The injected gas forms bubbles which ascend to the surface and produce the liquid metal foam floating on the melt. To achieve a certain stability of the foam the melt viscosity is adjusted by adding ceramic particles. The liquid foam can be drawn from the melt surface on a conveyor belt for cooling resp. freezing into solid state. Complex shaped parts can be produced by pouring or low pressure casting of the liquid foam into moulds [4].

The second main process route is the so-called powder metallurgical IFAM process (fig. 1), which in a way initiated the booming interest in metallic foams.

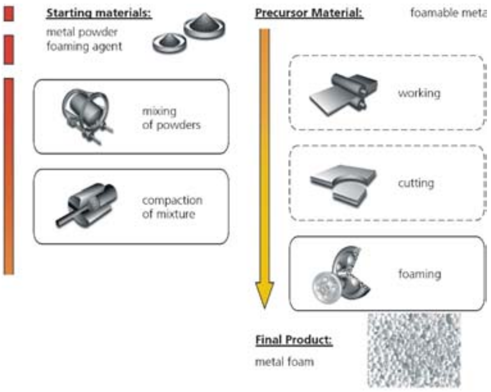

Fig. 1. IFAM process diagram

In this process a metal powder is homogeneously mixed with a foaming agent powder (e.g. metal hydride). The mixture is then compacted to achieve a dense semi-finished foamable precursor material. Heating above melting point leads to foaming agent decomposition. As soon as the metal melts the gas from the already decomposed foaming agent forms bubbles and expands the molten metal into a liquid foam. If this process is performed in a closed cavity, a near net shape metal foam part can be produced [5].

## 3. COMPOSITES AND PRODUCTION PROCEDURES

Composites containing metallic foam can be produced with all main classes of materials. An overview on discussed composite structures is given in fig 2.

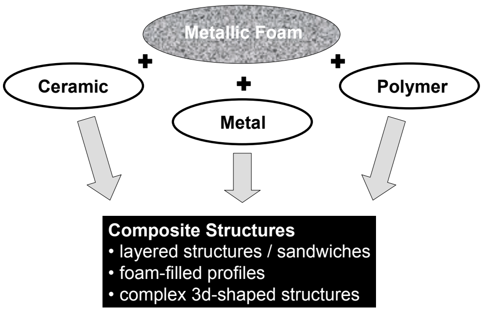

Fig. 2. Overview on discussed composite structures

The IFAM process enables the user to produce metal foam composites according to two general process routes.

The simplest route is the separate foam part production in a foaming mould. The foamable precursor material is inserted in a closed cavity (mould), expanded through heating above melting point, frozen by air cooling and finally removed from the foaming mould (fig. 3).

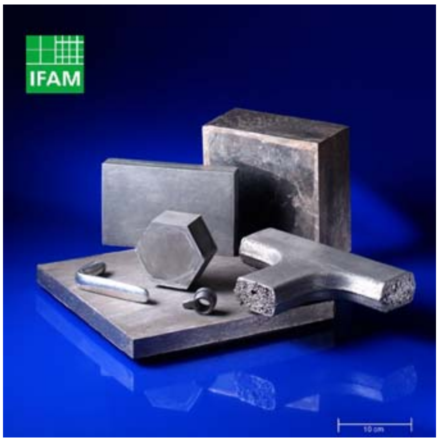

Fig. 3. Aluminium foam parts produced in a foaming mould by the powder-metallurgical IFAM process

To produce a composite these foam parts need to be joined to other components of the composite by additional process steps. The foam expansion process can be undertaken under optimised conditions and the other composite components are not affect by the foaming process. Through application of this process route all possible material combinations (metallic foam + ceramic, metal and/or polymer components) and types of composites (sandwiches, filled profiles and complex shaped structures) can be produced. Most commonly adhesive bonding will be employed for assembly but also welding, soldering or diffusion bonding is possible if only metallic or ceramic components are used. Metallic as well as polymer components can also be cast around the metallic foam core. The foam core is then mechanically fixed and, in case of combination with a polymer, adhesively bonded. Fibre reinforced plastics can directly be laminated and cured on metallic foams. In these cases the binding characteristics are comparable to adhesive bonding though no additional adhesive is necessary.

Alternatively the foamable precursor can be directly expanded (in-situ) in a hollow structure which first functions as a foaming mould and then works as a component of the composite structure. This procedure reduces the number of process steps and avoids the need for a foaming mould. Applicable component materials are ceramic and metal since polymer would not withstand the thermal load during the in-situ foam expansion process. Metal components need to have a significantly higher melting point than the metal to be foamed to avoid melting during foam expansion process. An example of an aluminium extrusion profile filled with aluminium alloy foam is displayed in figure 4.

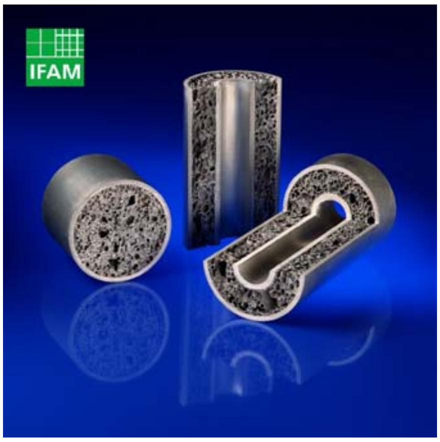

Fig. 4. Aluminium profile filled with aluminium alloy foam produced by in-situ foaming process

All types of composite structures (sandwiches, filled profiles and complex shaped structures) are producible according to this route. Especially if a complex three dimensional shaped hollow profile is to be filled with foam this process is advantageous. The profile can be designed in one piece since the foam core will be expanded in the final shaped profile. A split design consistent of two or more parts, which would be assembled around a separately produced foam core, is not necessary. Independent of the composite geometry a sintered or metallic binding between the foam and the remaining components can be achieved, though additional process steps like surface treatment before foam expansion and a precise process control are required for this purpose. In any case the whole structure will experience a heat treatment which can influence the mechanical properties of the non-foam components.

A variation of the described “in-situ” process route is roll-cladding the foamable precursor material to a non-foamable material before foam expansion. In that way a layered composite of foamable and non-foamable materials with a metallic binding between each layer can be achieved. Only metallic materials can be joined by that process since the formability of ceramic is too low and polymer materials can not be roll-cladded with metals. In addition, polymers would burn during the final heating for foam expansion. After optional cutting, forming and joining steps the layered composite is heated above melting point of the foamable layer for expansion. The conventional non-foamable layer(s) need to have a significantly higher solidus temperature to avoid melting during foam expansion. Cladding of one foamable with one non-foamable panel leads to a two layer composite which is used as a precursor material to produce foam-filled profiles with a metallic bonding between foam core and outer shell. Obviously the foamable layer needs to be positioned on the inside of the formed profile. While heating the foamable layer expands and fills the cavity of the shell structure, which consists only of the non foamable layer. Joining two conventional sheets on one foamable panel leads to a precursor for a so-called sandwich structure. By heating the foamable middle or core layer is expanded. If only aluminium alloys are employed the result is an aluminium foam sandwich panel (fig. 5), but other material combinations (e.g. steel surface layers with aluminium foam core) are also possible.

Fig. 5. Aluminium foam sandwich (AFS) formed and twisted before foam core layer expansion

Production of straight panels in any material combination and size depends on the formability of the employed materials, sufficient process control against melting of the surface layers and finally the available furnace size. If any roll-cladded precursor material is to be formed it has to be kept in mind that the roll cladding process strain hardens the surface layers. A heat treatment aimed at removal of this effect is possible to a limited degree. The foaming temperature of the foamable layer may not be exceeded. Heat treatment temperatures for steel is above aluminium (alloy) solidus temperature, a full recovery of forming capabilities for that face sheet material is impossible.

## 5. MECHANICAL PROPERTIES

### *5.1 FOAMINAL properties*

The characteristic properties of IFAM's metallic resp. aluminium foams (tradename FOAMINAL®) have been determined in several test series and projects. It was found that most of the properties strongly depend on the foam density resp. on the porosity of the cellular structure. With increasing porosity and, thus, decreasing density the mechanical properties also decrease significantly (example young's modulus in fig. 6). A collection of all data achieved is given in IFAM's properties overview [6].

One of the unique metallic foam properties, which drew a lot of interest on this materials class, is energy absorption and high energy absorption efficiency. Generally metallic foams deform like plastic foams under compression but at a force level one order of magnitude higher (fig. 7).

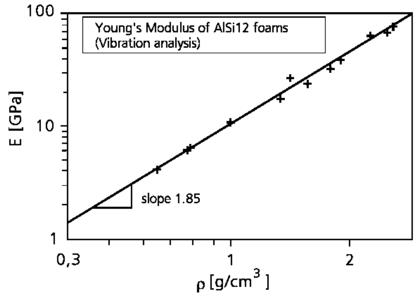

Fig. 6. Young's modulus in dependence of foam density

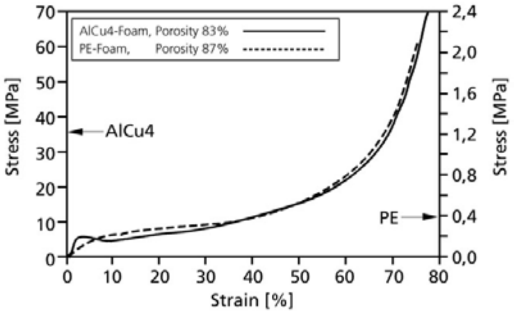

Fig. 7. Comparison of aluminium alloy and polymer foam in compression testing

Due to energy absorption at a constant force level over a wide deformation range the energy absorption efficiency is above 80 % for aluminium foams with approx. 20 % relative foam density [6].

### *5.2 Role of FOAMINAL's closed surface skin*

One feature of IFAM's foams is the closed surface skin with topology comparable to the surface of sand cast parts. It is understood that this surface skin influences the properties of the integral foam part (skin + cellular core) [6].

Strictly speaking such a foam part is already a composite of a more or less dense surface skin and a cellular or porous core. Up-to-date mechanical properties of different shaped foam samples with and without surface skin have been determined. These properties can be used for design and optimisation of foam parts but especially the mechanical behaviour of the surface skin and their influence on the overall properties of the foam part has not yet been finally clarified. The obvious procedure for determination of skin properties would be mechanical testing of skin samples. Due to the nature of the surface skin (wall thickness < 0.5 mm, rough surface topology, sporadic pores/holes) separation of a surface skin from a foam part is problematic. A satisfying solution to produce samples for mechanical testing could not be realised yet.

A general approach to implement the surface skin as one part of an IFAM foam has been developed by Hanssen et al [7]. A three point bending test on IFAM foam samples has been modelled by applying brick elements for the cellular core and shell elements for the surface skin (fig. 8). Through comparison of the bending performance of foam samples with and without surface skin and through application of basic beam formulations an equivalent surface skin thickness could be estimated. Mechanical properties of the skin material where approximated by data produced by tensile tests on the dense alloy. With this input data the three point bending test could successfully be simulated using LS DYNA. A good agreement between test and simulation results has been observed [7].

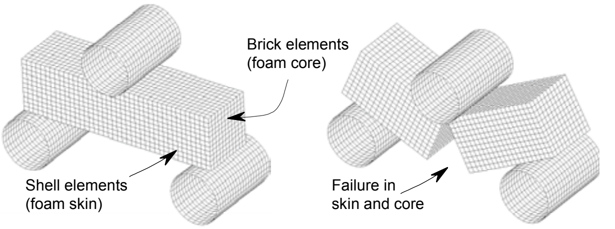

Fig. 8. Three point bending test of IFAM foam samples modelled with two different element types

*5.3 Foam filled profiles as energy absorbers*

The task of replacing conventional structures (e.g. hollow profiles) as energy absorbers in e.g. automotive or railway structures by metallic foams is complex. Most energy absorbing structures need to bear static as well as dynamic loads in normal use and absorb crash energy in the case of an impact/accident. As already discussed mechanical properties of foams are rather low compared to dense materials due to the high porosity level. One solution to make use of the extraordinary energy absorption capabilities of metallic foams is filling hollow structures with metallic foam. Ideally the outer shell structure can be reduced in cross section and wall thickness just to bear the static and dynamic loads. The foam core stabilises the shell structure against buckling and both components together absorber impact energy at a constant force level.

Hanssen [8] has investigated the mechanical properties of foam filled structures in compressive testing. It could be observed that the foam core in the profile influences the deformation behaviour of the profile. During compression the profile starts folding. The foam core inhibits folding to the inside of the profile. The fold length is decreased, the number of folds increases. This interaction between foam core and profile absorbs additional energy. For prediction of the plateau force level of the foam filled structure ($F_{composite}$) the superposition of the force for deformation of the single profile ($F_{profile}$) and of the single foam core ($F_{foam}$) has not been sufficient. An additional interaction effect term ($F_{interaction}$) need to be added:

$$F_{composite} = F_{profile} + F_{foam} + F_{interaction} \qquad (1)$$

The additional force through the interaction between foam core and profile depends on the mechanical properties and dimensions of the profile as well as the compression strength resp. the density of the foam core. Application of formulations from structure mechanics lead to (2):

$$F_{composite} = 13.06\sigma_0 b_m^{1/3} h^{5/3} + \sigma_f b_i^2 + C\sqrt{\sigma_f \sigma_0}\, b_m h \qquad (2)$$

$\sigma_0$ = profile material characteristic stress
$\sigma_f$ = foam plateau stress
b = outer width of profile
$b_i$ = inner width of profile
$b_m$ = b – h
C = interaction constant
h = profile wall thickness

Hanssen performed compression tests on empty profiles, separate foam cores as well as foam filled profiles with a positive fit between foam core and profile. Based on the test results input parameters for (2) were determined and the interaction constant was calculated. For square cross section foam filled profiles with foam cores made by the melt foaming route and a density between 0.17 and 0.34 g/cm$^3$ an interaction constant C = 5.56 at 50 % deformation has been determined. Calculated and measured plateau forces of the foam filled structure were in good agreement [8].

At IFAM Bremen similar tests have been run to verify Hanssen's concept for foam cores produced by the powder metallurgical IFAM process. Square cross section foam filled profiles were compression tested. Results of samples with a foam core of 0.57 g/cm$^3$ density and with a positive fit as well as an adhesive bonding to the profile are displayed in figure 9.

The test results reveal that profiles filled with foam produced by the powder metallurgical IFAM process show an interaction effect similar to profiles filled with a foam core made by the melt foaming process. In addition to Hanssen's work an influence of the intensity of the bonding between foam core and profile has been observed. Interaction constants for both types of bonding between foam core and profile could be determined. The interaction constant of foam cores with positive fit (C = 4.04) is lower than that of the adhesively bonded foam cores (C = 5.56).

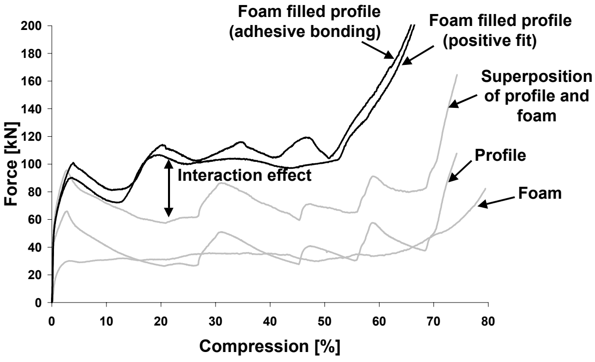

Fig. 9. Compression force versus compression of foam filled profiles (IFAM AlSi7 foam, 0.57 g/cm$^3$)

The adhesive bonding is an additional resistance for the profile against folding to the outside. In this test series the bonding ruptured before parts of the foam core could be drawn into the bulging fold. It is assumed that a more intensive bonding will lead to an increased interaction effect. In that case the local tensile strength of the foam will be lower than the tensile strength of the bonding. The foam core locally ruptures and a foam volume fraction will be drawn into the out-forming fold.

### *5.4 Sandwich materials*

A sandwich structure usually consists of two high stiffness and high strength face sheets or skins with a large volume and low weight core layer in between. The face sheet bear tensile and compression forces from bending loads. The core layer bears shear and compressive loads. Furthermore a high thickness core layer increases the sandwich's moment of inertia at low weight increment and supports the face sheets against buckling [9].

IFAM's aluminium foam sandwich (AFS) material ideally fulfils the described concept. Due to the metallic bonding between face sheets and foam core a maximum force transmission and thus best possible use of all components is assured. Comparing a flat panel of aluminium with an AFS panel of the same weight but with triple height the bending stiffness of the AFS is approximately one order of magnitude higher than the stiffness of the dense aluminium panel [10].

Furthermore the metallic bonding between face sheets and foam core makes the AFS superior to other adhesively bonded sandwich materials in terms of long term stability at room as well as elevated temperatures, flame resistance and emission of toxic substances [6].

## 6. APPLICATIONS AND FEASIBILITY STUDIES

### *6.1 AFS in automotive applications*

The superior weight specific bending stiffness of aluminium foam sandwich material qualifies this sandwich material for use in automotive structures. In a feasibility study a rear wall of the passenger cell of a CLK roadster has been produced based on aluminium foam sandwich. FEM simulations (fig. 10) with static torsional load on the rear wall showed that von Mises stresses in the AFS panel (left) are much more homogeneously distributed and also significantly lower than in the conventional steel panel (right). Additionally the AFS panel is 23 % lighter than the steel solution [11].

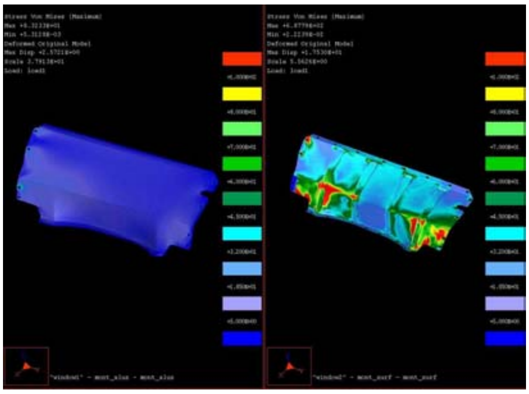

Fig. 10. Stress distribution in a rear wall panel of an automotive body structure under torsional load (left: aluminium foam sandwich panel, right: conventional steel panel)

### *6.2 Aluminium foam in suburban railcars*

Among the first aluminium foam parts in real-life applications is a crash energy absorber for suburban railcars (black part in the centre of fig. 11).

Fig. 11. Frontal view of suburban railcar with frontal crash energy absorber consistent of aluminium foam and polymer foam both covered by a rubber surface layer

This crash box is a composite structure of polymer and aluminium foam with a rubber surface coating. The component is specifically designed to meet the requirements of the internationally recognised recommendation VDV 152 of the German association of transportation companies [12]. Load cases considered include collisions of the railcar with track end devices as well as other railcars of similar type at low speeds between 3 and 5 kph. Besides absorbing a specified amount of energy, a number of additional requirements have had to be fulfilled. Based on design and technical needs a good overlap with opponent vehicles or structures in as many crash situations as possible is targeted. Since the railcar is employed in urban or suburban areas a certain level of pedestrians protection needed to be realised, which has been achieved by the rubber skin. Furthermore, a certain mounting concept with limited available mounting space allowing short replacement time and finally stringent cost targets were met by the advanced design solution.

The shown crash absorber design became the standard technical solution in that suburban railcar series and has already been sold world-wide. Slightly higher component cost due to the composite design of the component are easily compensated by major cost advantages in reduced repair effort after collisions have occurred [13].

### *6.3 Aluminium foam in fibre reinforced polymer structures*

Composites and sandwich structures with fibre reinforced polymers (FRP) are in use for several decades. The high stiffness as well as the high tensile strength make FRPs an ideal component for shell structures in complex 3d shaped composites or as face sheets in layered sandwich structures. However, thin walled hollow FRP structures are susceptible to buckling failure. With a low density aluminium foam core these structures can be stabilised with acceptable weight increment. Furthermore, the aluminium foam core can function as a permanent core on which the

FRP precursor can directly be laminated and cured. Due to the metallic matrix polymer curing temperatures do not influence the performance of the aluminium foam.

In a prototype of a lightweight and high performance golf caddy the frame to carry the golf club bag (fig. 12) was produced from FRPs. The curved parts of the frame contain an aluminium foam core for stabilisation of these highly loaded areas [14].

Fig. 12. Golf caddy with aluminium foam cores for stabilisation purposes in the curved sections of the one piece frame work design

## 7. CONCLUSIONS

Aluminium foams can be combined with all other material classes to form composites making use of the characteristic properties of each component. The combination of thin surface skins (in sandwich structures) or a complex shaped thin walled shell structure with a low density aluminium foam core are preferred solutions for structural as well as energy absorption applications. Usually the outer dense materials bear high tensile and compression stress in static and dynamic load cases. The inner aluminium foam core stabilises the thin face sheets / shell structure against buckling. Through the in-situ foaming technology composites with a metallic bonding between the dense face sheets / shell and the cellular aluminium foam can be produced. This most intense bonding type allows maximum force transmission between both composite components and additionally reduces the number of process steps in production.

Mechanical properties of composites with aluminium foam are not a simple superposition of the single components properties. In energy absorption of aluminium foam filled structures an additional interaction effect could be observed which further increases the weight specific energy absorption of that composite. Analytical as well as numerical approaches for prediction of energy absorption are established for aluminium foams made by the melt foaming route. These approaches could be transferred to IFAM's powder metallurgical aluminium foams. Furthermore a new approach to include the surface skin of IFAM foams in component dimensioning considerations has been developed and verified by experimental tests.

Examples of real-life composite structures containing IFAM's aluminium foam show examples of promising application areas. Overall IFAM's aluminium foams are on the way to large scale production.

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