Chapter 5
Light-Weighting in Transportation and Defence Using Aluminium Foam Sandwich Structures

J. Banhart, F. García-Moreno, K. Heim and H.-W. Seeliger

Abstract We review the status of Aluminium Foam Sandwich (AFS) technology and discuss both recent improvements of foaming technology and current applications. It is concluded that the quality of foams has improved in the past years and costs are slowly decreasing. This is why applications in which metal foams have more than one function are more likely to be economically viable. The examples presented here include battery cases for electric cars, crash absorbers, high-speed train front heads and blast protectors for vehicles and tanks.

Keywords Transportation · Defence · Light-weight structure · Aluminium foam · Sandwich panel

5.1 Introduction

Aluminium Foam Sandwich (AFS) is a product comprising a highly porous aluminium alloy foam core and two aluminium alloy face sheets. The layers are firmly attached to each other by metallic bonding. Use of such sandwich panels has been proposed for many industrial sectors including automotive (Degischer and Kriszt 2002; Banhart 2005), ship building (Banhart et al. 1998), railway and aircraft industry (Yu et al. 1998). Sandwich panels compared to dense material or bare foam have various advantages. They are stiffer than dense sheets of equal mass (Ashby et al. 2000). Compared to bare foam without face sheets the main advantage is that the outer skin allows the sandwich to bear tensile loads that occur, e.g. when the panel is bent. Bare metal foam alone performs poorly in tension and panels fracture quickly on the outer side. Aluminium foams reinforced with metal wires or meshes (Simančík et al. 2001, 2002) improve this situation similarly to AFS. They lead to better tensile properties but are less efficient in accommodating compressive stresses. In sandwich

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panels, the porous foam core is hidden inside a dense material which avoids possible problems with surface damage or corrosion. Provided the edges are sealed the aluminium foam can be completely inaccessible to liquids and gases. Compared to sandwich panels where face sheets are merely glued to a sheet of metal foam, the pure metallic character of AFS is an advantage whenever flammability, heat resistance, weldability, recyclability or long term stability are an argument. In the following, we shall briefly review the advances in manufacturing technology and describe a number of promising applications of AFS in transportation and defence.

5.2 Manufacture of Aluminium Foam Sandwich Panels

Manufacture of AFS is based on the expansion of metallic precursors driven by the decomposition of an embedded blowing agent ('P/M process') (Allen et al. 1963). Such precursors allow for filling complex moulds and producing shaped parts of all kinds. They can also be used to bare foam plates provided that suitable moulds are available. If sandwich panels are required, metallic face sheets can be bonded to such plates.

The AFS technique is mould-free and does not require any bonding step. Here, a three-layer composite comprising a central foamable layer made of consolidated metal powder/blowing agent mixtures and two solid face sheets is used, see Fig. 5.1. Upon heating to a temperature high enough to foam the lower-melting core layer but low enough to prevent the higher-melting face sheets from liquefying, the composite expands to an AFS panel (Baumeister et al. 1994). Bonding between core and face sheets is metallic both before and after foaming. To ensure flatness of the resulting AFS, a hot calibration step after foaming is recommended. All manufacturing steps on an industrial scale are shown for better understanding in Fig. 5.2: Powder filled ingots, rolling process, rolled three-layer composite precursor, foaming furnace.
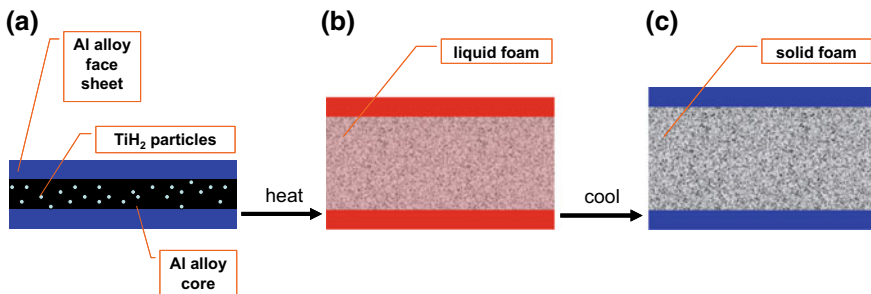

Fig. 5.1 Principle of AFS manufacture. **a** Three-layer composite with a central core layer made of a compacted mixture of metal powders and blowing agent powder, mostly thermally modified TiH_2. **b** Composite expanded upon heating. Only the core changes its volume, whereas the face sheets remain unchanged. **c** Fully expanded and solidified AFS after cooling
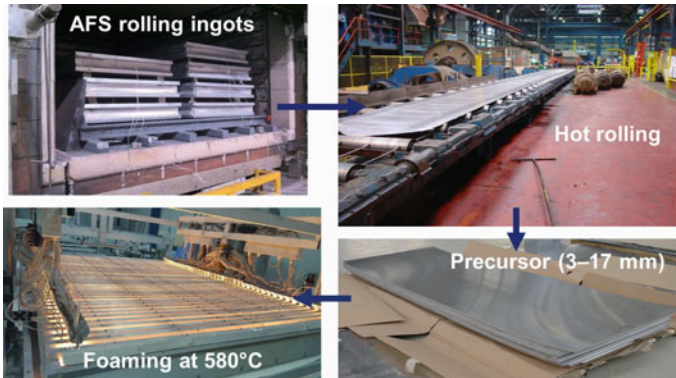
Fig. 5.2 Images taken from various stages of AFS precursor manufacture. Upper left: Powder-filled ingots read for rolling, right: rolling process, lower right: rolled three-layer composites after rolling and cutting, lower left: foaming furnace

The advantages of such an integrated process include the absence of any non-metallic bonding, the intrinsic non-flammability and the option to create 3D-shaped parts by pre-forming the three-layer composite prior to foaming or by hot calibrating the AFS after foaming (Banhart and Seeliger 2008). Disadvantages include the restricted set of possible alloy combinations for the core and face sheet due to the necessity to coordinate the melting temperatures of the core and the face sheets, the need to use expensive metal powders and the high number of processing steps. Possible ways to overcome the problem have been discussed (Banhart and Seeliger 2008), but up to now no viable solution has been demonstrated.

The alloy combinations that have been in use for both core and face sheets until a few years ago are listed in Table 3 of Banhart and Seeliger (2008). In most cases, the alloy AlSi6Cu4 or AlSi6Cu6 was used for the expandable core, since this alloy starts to melt at 524 °C, which is low compared to the melting point of the face sheet materials applied (different commercial 1000, 3000, 5000 and 6000 series alloys). However, copper is heavy, expensive and causes corrosion. Therefore, replacement was sought and found in the system Al-Mg-Si (Helwig et al. 2011). Among various suitable alloys the alloy AlSi8Mg4 (±1 wt% for Mg and Si) is one with outstanding foaming behaviour (good expansion, small and regular pores) (Helwig et al. 2011) and is in general use now. Another advantage of replacing Cu by Mg is the improved corrosion resistance (Fig. 5.3).

A key point for the improvement of foam quality in recent years has not only been the choice of a new alloy but also a very precise conditioning of all metal powders used. Contaminations, especially by atmospheric moisture or dust have to be avoided since those were found to have adverse effects on the uniformity of pore size distributions of foams made from such starting materials. The explanation for such effects is that the bonding of individual powder particles during compaction is compromised by chemical adsorbates or impurities at the powder surfaces, which then leads to

Fig. 5.3 1×1 m^2 large AFS sliced in the panel plane

weak points in the structure. When the gas evolving from the blowing agent (hydrogen when TiH$_2$ is used) inflates the bubbles and expands a powder compact during foaming, large pores can be formed at such weak points. Such pores can be larger than the thickness of an AFS under unfavourable conditions, have an adverse effect on mechanical properties and also give rise to an undesirable appearance, see Fig. 5.4 (top). In contrast, AFS panels exhibiting a favourable pore structure expressed by a predominant pore size in the range of 1–1.5 mm and only few larger pores are obtained after tuning the process parameters accordingly, Fig. 5.4 (bottom).

Another key point is the foaming process. A fully controlled and automated array of infrared heating lamps was found essential for foaming large panels. Temperature gradients above ~15 K across the entire surface lead to premature foaming (e.g. in the middle) and corresponding damage of the pore structure by propagating cracks and/or an undesired variations of pore size.
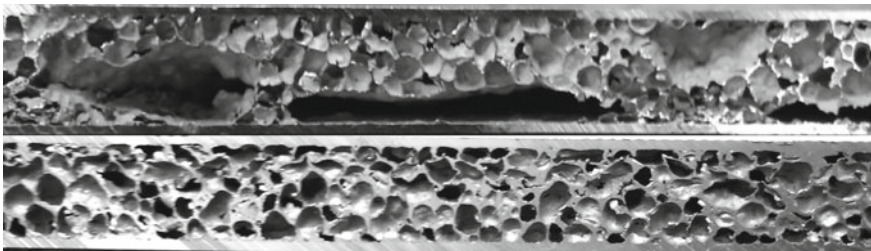

Fig. 5.4 (Top) AFS made without carefully adjusting the powder and processing parameters and exhibiting individual large pores. (Bottom) AFS made by applying the current knowledge concerning especially powder degassing. Thickness of panels is ~10 mm

Table 5.1 Basic data of commercial AFS material (taken from Pohltec Metalfoam GmbH 2017)

Parameter	Range
AFS sheet size	Max. 2500 × 1100 mm
Total thickness	9–80 mm
Face sheet thickness	0.65–10 mm
Flatness of AFS	1 mm/1000 mm
AFS thickness tolerance	±0.5 mm
Cover sheet alloys in use	3103, 5005, 5754, 6082
Core alloys	AlSi6Mg3, AlSi8Mg4, AlSi6Cu6

5.3 Products

AFS can be intrinsically large and much effort has been put into up-scaling of both precursor manufacture and foaming equipment. The maximum size currently achievable is 2500×1100 mm^2 (Pohltec Metalfoam GmbH 2017). This is not a fundamental limit but given by restrictions in producing three-layer composites with 1100 mm width—restricted mainly by the rolling step—and the difficulty in heating a large panel up from room temperature to the foaming temperature around 600 °C while keeping the temperature everywhere within a certain margin. Figure 5.3 shows a large panel of AFS than has been cut open along the central plane and demonstrates the absence of abnormally large pores and other defects over this large area.

The annual production rate of one such foaming furnace is currently 9000 m^2, extendable to 20,000 m^2 by introducing production around the clock. Some basic data of such materials are summarised in Table 5.1. Costs have been slightly decreasing in the past few years. How much a given AFS panel costs depends on the exact foam/face sheet configuration and the production volume.

5.4 Principles of AFS Application

Light-weighting involves reducing the mass of a component while keeping its mechanical properties at the required level. The property in question is often stiffness but other properties can also be a target for optimisation. There are three groups of properties which are favourable in metallic foams (Banhart 2005):

- Elastic properties: Young's (E) and other moduli (e.g. G) of metal foams usually scale with $(\rho^*)^2$, where ρ^* is the apparent density of a foam,
- Plastic properties: foams collapse at a nearly constant stress and the associated collapse strength σ_c also scales with a power of ρ^*,
- Functional properties of metal foams involve thermal and electrical transport coefficients, electromagnetic or acoustic damping etc. Some of them are directly related to ρ^* but also might depend on cell morphology in a complex way.

Table 5.2 Stiffness optimisation of a 1×2 m^2-large panel. The reference point is a steel sheet of a given stiffness which is replaced by aluminium, CFRP and AFS (face sheet material = alloy 6082)

	Steel	Aluminium	CFRP	AFS
Required thickness for equal stiffness [mm]	4.7	6.8	5.6	8.0
Mass [kg]	73.3	36.6	17.0	12.8
Mass reduction [kg (%)]		−36.7 (50%)	−56.3 (77%)	−60.5 (83%)
Cost [€ (₹)]	73 (5500)	109 (8200)	510 (38000)	128 (9600)
Cost/1 kg mass reduction w.r.t steel [€ (₹)]		1 (75)	7.7 (580)	0.9 (68)

The bending stiffness S of a slab of foam scales with h^3, where h is its height, and the apparent young's modulus E^*. Consider foaming a dense precursor sheet that can be foamed in the thickness direction by heating. The mass of this sheet is nearly constant as gas is released from the blowing agent, bubbles are formed and the height of the foam increases. As $E \propto \rho^2$ and $\rho \propto h^{-1}$, stiffness increases linearly with h: $S \propto h$. Thus foaming at a constant mass increases stiffness and metal foams are stiffer than metal sheets of the same mass. Table 5.2 compares such a stiffness optimisation using a steel sheet of a certain size and mass as a reference point and replacing it by different materials including AFS. Clearly, AFS offers the highest potential for mass reduction.

The optimisation process is a lot more complicated when other properties are involved. For example, the plastic deformation behaviour can be an important issue as well as other functional properties and no simple comparisons such as in Table 5.2 can be given.

Beside material's properties of AFS technological or economical properties can limit or favour application. For example, the fact that AFS can be machined, cut or welded similar to conventional aluminium material facilitates application.

5.5 Application Examples

5.5.1 Battery Case for Electric Cars

In traditional combustion engine driven cars, the body-in-white (BIW) has been in general the same for decades and has been developed mainly under the viewpoint of the use of aluminium alloys or steels. The integration of AFS or even any other metal foam into this highly optimised system is therefore very difficult. AFS provides an excellent weight-saving potential of up to 70% while keeping the bending stiffness constant. However, it is a novel and complex material just by its dimensions: the thinnest AFS consists of 6.5 mm foam and two 0.75-mm thick face sheets (8 mm
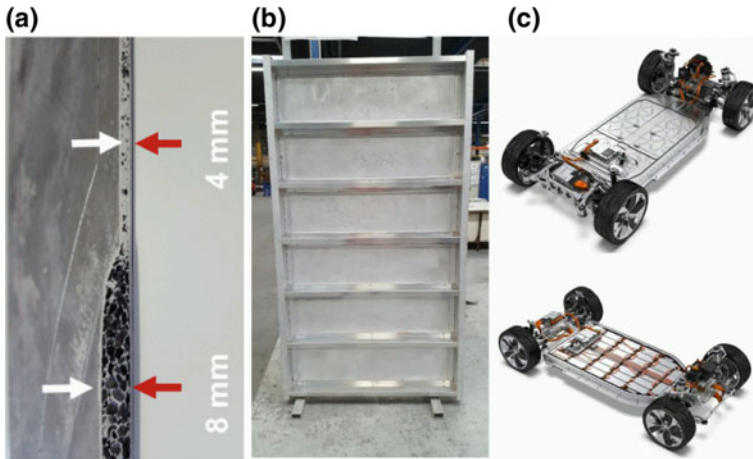
Fig. 5.5 Concept of underbody and battery compartments of an electric vehicle. **a** Compressed AFS panel used to obtain sealed edges, **b** module comprising underbody (reverse side) and battery compartments (obverse), **c** location of prototype in electric car (Jaguar I-pace concept car)

total thickness). Hitherto, in standard BIWs, metal sheets of 1–3 mm thickness have usually been employed. Therefore, a direct substitution of traditional sheet-based structures by AFS would lead to an overdesign and be economically not reasonable.

For electric cars, the design is still not clear and various conceptual lightweight construction solutions are possible. The absence of a large engine in the front (or back) of the vehicle and the necessity to transmit power to the wheels from there allows for a flat underbody construction—which is the first criterion facilitating a reasonable use of AFS. Electric engines can then be placed on the axes directly. On the other hand, the batteries represent a large fraction of the mass of the vehicle and require a lot of space and have to be accommodated. One simple but very promising design, which might establish a standard for most electric cars, is shown in Fig. 5.5b, c. In this "skateboard" design, the batteries occupy the space between the underbody sheet, the passenger compartment floor and the wheels. In this way, the centre of gravity is kept low, thus improving the dynamics of driving. The two sheets (underbody and passenger compartment floor) can be separated by vertical struts and in this way stiffness is improved. The traditional design used for most of the battery compartment modules consists of a multilayer structure of various Al or steel plates fulfilling various requirements (e.g. impact protection, cooling, bracing, etc.). While this is a viable solution, it adds considerable mass to the car. Along the principles outlined in the previous section an alternative solution based on AFS was designed. The AFS concept battery compartment consists of an underfloor (final layer to the street) and floor panel (border to the passenger cabin). Both were made of AFS and were bonded to extruded aluminium alloy profiles by punch rivets and automotive adhesive, see Fig. 5.5b. Partial densification of some AFS areas, see Fig. 5.5a, was carried out to seal the elements and to connect them to the substructure by using standard connection

techniques (riveting, glueing, etc.). However, the largest part of the AFS was not densified. This procedure led to an increased stiffness and impact protection, while mass was reduced. Thus, the mass-specific properties were improved. Figure 5.5c shows how the battery compartment integrates into a Jaguar I-pace concept car.

Further essential aspects that make AFS appear a suitable replacement for steel or aluminium alloy sheets are improved structural and functional properties besides stiffness, namely:

- Higher damping of electromagnetic radiation (EMC compatibility),
- More safety in the case of a battery failure,
- Protection of the battery from external impacts, especially from puncture by sharp objects,
- Improved sound and vibration damping,
- Additional crashworthiness.

Moreover, the fact that the material can be used in the assembly process of a vehicle in a very similar way as bulk aluminium applying standardised and proven production techniques is an additional advantage.

5.5.2   Crash Absorbers

New trends and developments in the automotive industry, especially in the electric car segment, increase the demand for new concepts and materials for lightweight construction. Furthermore, new car designs are necessary due to the rearrangement of components, making it possible to consider cellular materials from the beginning. Passenger safety is another important factor, where a light, as compact as possible but very effective crash protection system is needed especially because the available crash space is reduced due to the absence of the traditional front engine. An example is shown in Fig. 5.6. Metal foam parts developed by the Technical University Berlin and Pohltec Metalfoam are foreseen in the prototype of an ultra-light electric vehicle recently developed in the European project 'Evolution' by a number of companies including Cidaut (Valladolid, Spain), Pininfarina (Cambiano, Italy) and Pohltec metal foam (Cologne, Germany).

5.5.3   High-Speed Trains

Railway industry is an important factor in future mobility concepts. Promising prototypes have evolved in the past years as possible future serial application.

AFS foam panels delivered by the IWU (Chemnitz, Germany) have been used in the floor of a wagon of the metro in Peking in continuous operation without issues since 2008. Among their advantages shared with other applications, the property of
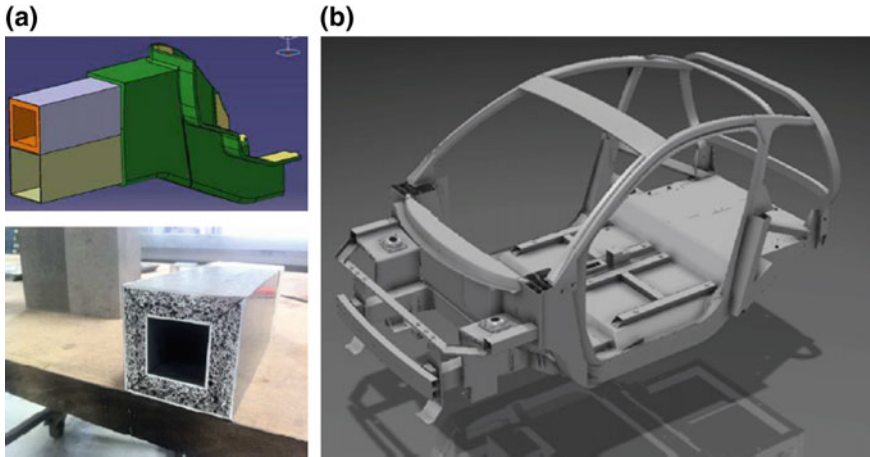
Fig. 5.6 a Crash absorber box of the electric car prototype developed in the European project 'Evolution'. It is made of rectangular aluminium alloy profiles filled with Al-foam. **b** CAD design of the body in white (Garcia-Moreno 2016)

being not hygroscopic and the acoustic properties that are similar to those of wood have been named (Hipke 2016).

A train front structure was welded from curved AFS plates by the Wilhelm Schmidt GmbH (Groß-Kienitz, Germany) in cooperation with the Brandenburgische Technische Universität Cottbus (BTU, Cottbus, Germany) (Sviridov et al. 2012; Viehweger and Sviridov 2007). A more prominent and recent prototype is the power head cover of the Intercity-Express-Train (ICE) train fabricated by Voith Engineering (Ludwigsfelde, Germany) and IWU (Chemnitz, Germany). It is made of welded AFS plates and carbon fibers in the front, with a total length of around 6 m (Fig. 5.7). A mass
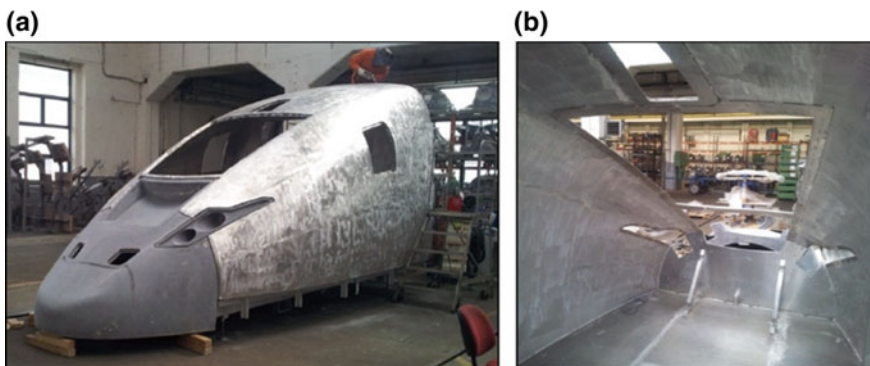

Fig. 5.7 a Prototype of German high velocity train ICE made of welded aluminium foam sandwich. **b** View of the interior demonstrating the low number of components required (courtesy of Thomas Hipke, IWU, Chemnitz, Germany and Voith Engineering, Chemnitz, Germany)

reduction of 18% was achieved while maintaining stiffness at the same level, thus improving vibration damping and additionally reducing the number of manufacturing steps compared to the traditional construction procedure. These examples clearly show the advantages of metallic foams or AFS panels against honey comb panels, especially when curved sections are required.

5.5.4 Protection Against Blasts, Bullets and Other Hazards

Protection against bullets and explosions requires special material combinations. A combination of AFS with a stone plate has proved to be efficient to stop bullets fired from NATO and Kalashnikov guns. The hard stone front plate fragments the bullet and the following aluminium sheets and foam on the back stop the fragments and dissipate energy, see Fig. 5.8a, b.

Use of metal foam for armour has been suggested before for various configurations (Gama et al. 2001) but the combination stone/AFS is especially attractive for architecture: The AFS sheet is a convenient light carrier material and allows for fixing the structure. The stone is the material that can be displayed. The anticipated use is on or in buildings such as banks or in public building under threat. As there is little ageing and corrosion in AFS structures, outdoor use is possible without any problems.

Fig. 5.8 Composite of an AFS panel with a polished granite front plate hit by a bullet. The AFS had 1.8 mm face sheets and a 20 mm foam core, while the granite plate was 8 mm thick
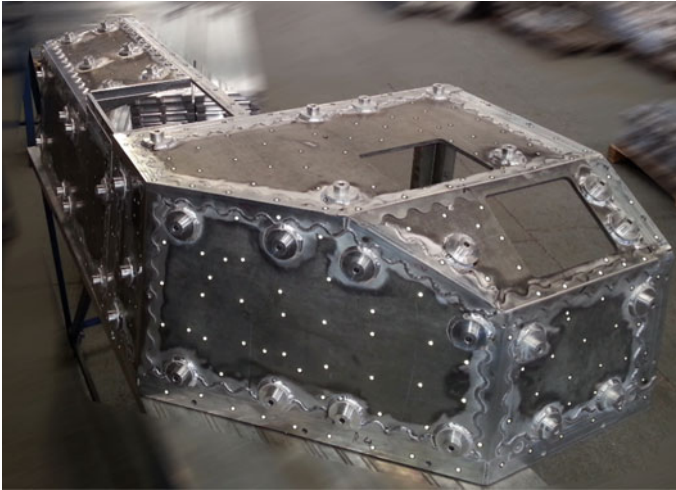
Fig. 5.9 Ammunition hood of a reconnaissance tank

5.5.5 Ammunition Hoods for Armoured Reconnaissance Tanks

AFS has found application in military vehicles. Selected reconnaissance tanks have been equipped with ammunition hoods to reduce their mass. The background for this was the requirement to reduce mass to a level that various such tanks can be transported in aeroplanes at a time. Such an ammunition hood is shown in Fig. 5.9. AFS is used in the wall areas and serves as first safety unit and a carrier for a bullet-proof Kevlar plate, see cylindrical attachments on AFS panels in Fig. 5.9. In this way, the total mass could be reduced by 80 kg, which in turn leads to a more efficient use of the transport capacity of the military aeroplane.

5.6 Outlook

Aluminium foam and here especially aluminium foam sandwich (AFS) technology has led to a number of promising small-scale applications. What is important for the development of the market is the availability of materials in quantities of tens of thousands of m^2 annually. Experience has shown that without a reliable source of material the search for applications in companies is slow which, in turn, slows down the development of manufacturing technologies. This is the well-known 'chicken and egg problem' of new materials.

The past years have seen an improvement of foam quality. Pore size distributions are now more uniform and large pores can be avoided. The cost of the product has been reduced slightly in the past. Strategies to bring costs further down include

combining various process steps into fewer integrated steps, e.g. to combine powder consolidation and rolling as suggested in Banhart and Seeliger (2008). Such integrated technologies have been found to be difficult to control and sometimes have a negative impact on foam quality but still they are the right way to go. Lightweighting in the transport and military sector is a challenging but also rewarding area of application for aluminium foam sandwich panels.

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