Recent Trends in Aluminium Foam Sandwich Technology

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We review the status of Aluminium Foam Sandwich (AFS) technology and discuss both recent improvements of foaming technology and current application strategies. It is concluded that the quality of foams has improved in the past years but the costs are still very much the same. This is why applications in which metal foams have more than one function are more likely to be economically viable. The examples presented include electromagnetic shielding, carrier plates for mirrors, cooking equipment, architectural panels and blast protection.

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 [1,2], ship building [3], railway and aircraft industry [4]. Sandwich panels compared to dense material or bare foam have various advantages. They are stiffer than dense sheets of equal mass [5]. 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 [6] improve this situation similar to AFS. Both lead to better tensile properties but are less efficient in accommodating compressive stresses. In sandwich panels, the porous foam core is hidden inside a dense material which avoids possible problems with surface damage or corrosion. If 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 inflammability, heat resistance or long term stability are an argument. It then opens many fields of application. In the following, we shall briefly review the advances in manufacturing technology and describe a number of promising applications of AFS.

2. Industrial Implementation of AFS Technology

2.1 Manufacture of AFS

Manufacture of AFS is based on the expansion of metallic precursors driven by the decomposition of an embedded blowing agent ('P/M process') [7]. Such precursors allow for filling complex moulds and producing shaped parts of all kinds. They can also be used to foam plates of foam provided that suitable moulds are available. If sandwich panels are required, metallic face sheets can be bonded to such plates.

The AFS technique, however, is mould-free and does not require any bonding step. Here, a three-layer composite comprising a central foamable layer and two solid face sheets is used, see Figure 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 [8]. 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.

The advantages of such an integrated process include the absence of any non-metallic bonding, the intrinsic non-inflammability 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 [9]. Disadvantages include the restricted set of possible alloy combinations for core and face sheet due to the necessity to coordinate the melting temperatures of the core and the skin, the need to use expensive metal powders and the high number of processing steps. Possible ways to overcome the problem have been discussed [9], but up to now no viable solution has been demonstrated.

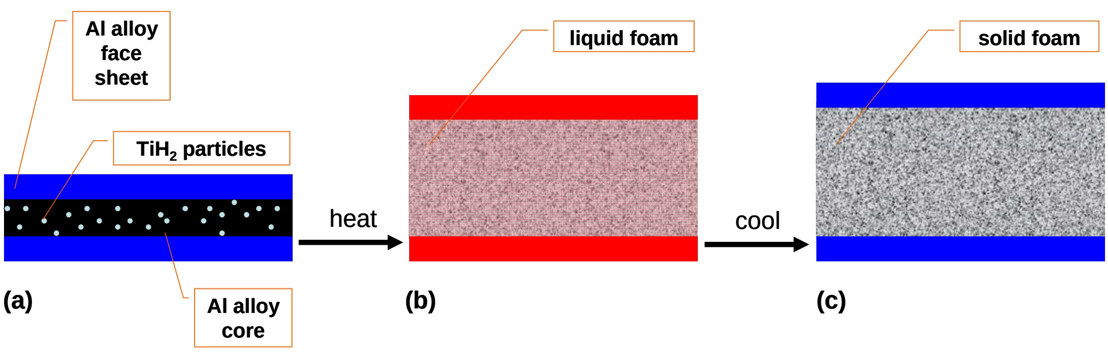


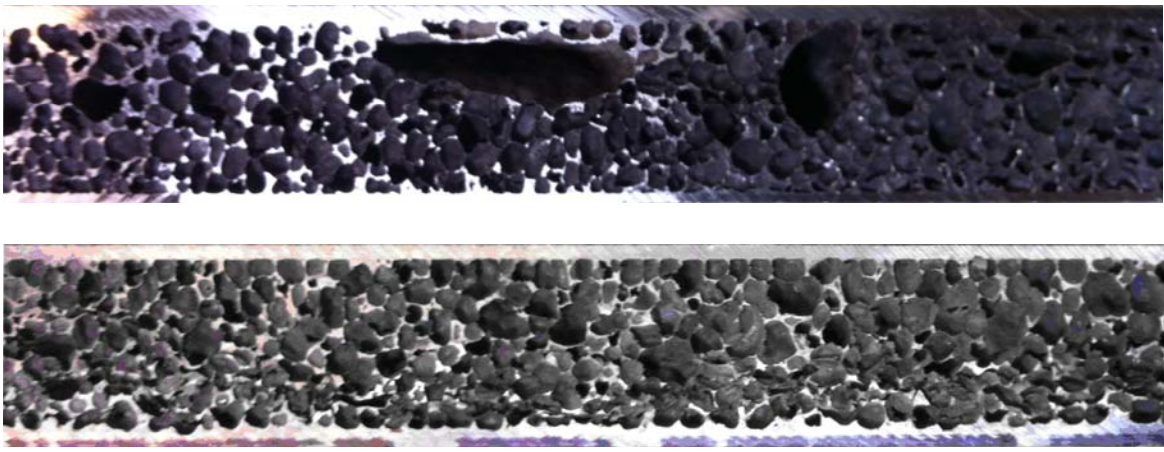
Figure 1. Principle of AFS manufacture. (a) Three-layer composite with a central core layer made of a compacted mixture of metal powders and blowing agent powder, mostly thermally modified TiH_2. (b) composite expanded upon heating. Only the core is changing its volume, whereas the face sheets remain unchanged. (c) Fully expanded and solidified AFS after cooling.

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 Ref. [9]. In most cases, the alloy AlSi6Cu4 or AlSi6Cu6 was used for the expandable core, since this alloy melts 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, a replacement was sought and found in the system Al-Mg-Si [10]. Among various suitable alloys the alloy AlSi8Mg4 is one with outstanding foaming behaviour (good expansion, small and regular pores) [11] and is in general use now. Figure 2 demonstrates the favourable pore structure of AlSi8Mg4 foams expressed by a predominant pore size in the range of 1 to 1.5 mm and few larger pores.

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 to or impurities at the powder surfaces, which then leads to weak points in the structure. When the gas evolving from the blowing agent (hydrogen when TiH_2 is used) expands the structure during foaming, large pores can be formed at such weak points as the material opens along various such points. Pores can be larger than the thickness of an AFS under unfavourable conditions and have an adverse effect on mechanical properties and also an undesirable appearance, see Figure 3.

Another advantage of replacing Cu by Mg is the improved corrosion resistance. Comparison of two foams after exposure to 24 h of salt spraying shows the much lower level of corrosion in the Cu-free foam compared to the Cu-containing one, see Figure 2b,c. In AlSi6Cu6 foam the entire surface has turned from initially light gray to dark during salt spraying, whereas the changes in AlSi8Mg4 are much smaller.

Figure 2. (a) Example of an AlSi8Mg4 foam. (b,c): Two foam samples prepared by cutting an AFS apart along the centre plane. Foams were exposed to salt spraying for 24 h (neutral salt spraying Test according to EN 9227 /ASTM B117). (b) AlSi8Mg4 foam, (c) AlSi6Cu6 foam.



(a)

(b)

Figure 3. (a) AFS made without carefully adjusting the powder and processing parameters and exhibiting individual large pores. (b) AFS made by applying the current knowledge concerning especially powder degassing. Both AFS: 33 mm foam core and 1.8 mm face sheet thickness

2.2 Products

AFS can be intrinsically large, and so much effort was put into up-scaling of both precursor manufacture and foaming equipment. The maximum size currently achievable is 2500×1100 mm^2 [12]. This is not a fundamental limit but given by restrictions in producing three-layer composites with 1100 mm width – given 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 maintaining the maximum temperature difference across the entire surface below 15 K throughout foaming. A fully controlled and automated array of infrared heating lamps was used for this purpose. Temperature gradients above this level lead to premature foaming (e.g. in the middle) and corresponding damage of the pore structure by propagating cracks and/or an undesired variation of pore size. Figure 4 shows a large panel of

AFS and demonstrates the absence of abnormally large pores and other defects over this large area.

Figure 4. 1×1 m^2 AFS sliced in the panel plane.

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 1.

Table 1. Basic data of commercial AFS material (taken from [12])

parameter	range
AFS sheet size	max. 2500 x 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	ASi6Mg3, AlSi8Mg4, AlSi6Cu6

3. Current Applications of AFS

In addition to the applications already described previously [9] we shall present results of recent applications studies carried out in the past 3 years.

3.1. Electromagnetic shielding

AFS material has a high stiffness-to-mass ratio. Therefore it is well suited for building light-weight structures that can bear loads while their deformation remains small. AFS has the additional useful functionality that it shields electromagnetic waves very well. Mobile telephone nets rely on a large number of wireless relay stations and transmitters placed on high masts. Such transmitters have to be shielded electromagnetically in order to avoid an adverse effect of the radiated electromagnetic pulses on the electronics and computers of the relay stations. In addition, the shielding has to bear forces by strong winds and have a good electrical conductivity around the entire circumference. This application profile makes AFS an interesting candidate material, which is why prototypes of the kind shown in Figure 5 have been developed.

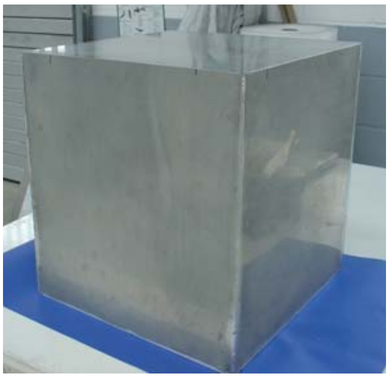


Figure 5. Damping box for electromagnetic waves made of aluminium foam sandwich (AFS). Size is 1200×600×600 mm^3.

Electromagnetic damping values as good as –118 dB were measured in the frequency range from 100 to 500 MHz for a box made of 15 mm AFS with a core density of 0.48 g cm^{-3}. A box made of aluminium sheet of the same weight exhibited a damping value of –57 dB. The values measured for the AFS agree well with those determined for open-celled Al foam of 14 mm thickness [13]. Therefore, AFS is a good candidate for such applications since it provides good electromagnetic damping, mechanical rigidity and electrical conductivity at the same time, i.e. is multi-functional. Starting off the application, however, will be challenging due to the very high number of boxes initially required, which could sum up to an annual need of 200,000 m^2 of AFS material.

3.2. Solar thermal energy generation

Solar thermal energy is a technology for harnessing solar energy for heat production and eventually generation of electricity. One design is that of a parabolic trough mirror, where light is concentrated onto a glass tube containing a fluid collector running along the axis of the trough in the focal line. The trough is parabolic along one axis and linear in the other, see Figure 6b. The trough can be tilted in one direction. Solar thermal power stations exist, e.g., in Spain and in desert regions of the USA and new ones might be built soon in North Africa.

One possible concept for a parabolic mirror involves AFS that can be bent to the large radii required (about 20 m) with low tolerances, see Figure 6a. A thin reflecting foil on top of the AFS trough would provide the high reflectivity needed. AFS is a suitable material since it is polymer-free. Unlike polymers, large amplitudes in temperature from + 60°C to 0° from day to night time would not affect AFS and a long lifetime is ensured. Thermal warping is small. The high stiffness-to-mass ratio is favourable to lower deformations caused by the wind and to ease moving the mirror. Parabolic troughs are just one possible concept. Fresnel mirror arrays consisting of many smaller flat mirrors could of course also benefit from the advantages of AFS too.

(b)

(a)

Figure 6. (a) Base plate for a parabolic mirror made of aluminium foam sandwich (AFS), 1500 mm long. (b) Solar thermal power plant showing a possible arrangement of mirrors (parabolic trough solar collectors at Kramer Junction in the Mojave desert in California (USA)) [14].

3.3. Cooking

AFS are useful materials for cooking equipment due to the characteristics of thermal conduction. A point-like heat source directed onto one side of the AFS, e.g. a gas flame, will first heat up the face sheet. Since the heat conductivity of the dense face sheet is 30 times higher than that of the foam, heat will be first conducted across the sheet. Diffusion of heat through the foam core will take place at a lower but still high enough rate. After arriving at the opposite sheet, heat will be dissipated in the plane of the face sheet plane again. AFS are therefore efficient heat diffusers. In addition, the total thermal capacity of the plate is low, i.e. little heat is stored in the plate. This is the reason why AFS has been proposed as a material for cooking utensils such as frying pans or saucepans [9,15].

Figure 7a shows a barbecue plate consisting of an AFS plate cut into shape. The margins of the plate were closed by the hot forming technique introduced in Ref. 9. A plasma coating was applied to prevent sticking [17]. Figure 7b shows an AFS replacement of a ceramic plate in baking ovens as they are being used in extremely rural environments. These are usually operated with fire wood. Due to the excellent heat diffusion and conduction properties and low thermal mass of AFS, 50% energy can be saved compared to a traditional ceramic plate and heating time reduced to 2 min. Moreover, no cracking can appear. UNESCO and the German Technical Cooperation have tested prototypes in Ethiopia and there are plans to manufacture 175 000 pieces.

Figure 7. (a) AFS barbecue plate surface coated, (b) simple cooking plate for wood fire oven.

3.4. Architectural panels

Materials in architecture have to combine functions and visual appearance. Architecture is a classical application field for metal foams, e.g. for their sound absorbing properties [16]. AFS are flexible to use, easy to process, non inflammable, light and robust and have a good corrosion resistance. They can be cut into halves along the plane of an AFS, thus exhibiting the open porosity to the viewer and using the dense back sheet to fix the panels. Fastening can be carried out using the same techniques used for conventional architectural aluminium panels. This lowers costs, does not require additional certification and increases safety in the case of fires. If the AFS panels are used as a whole, their surface can be modified as shown in Figure 8.

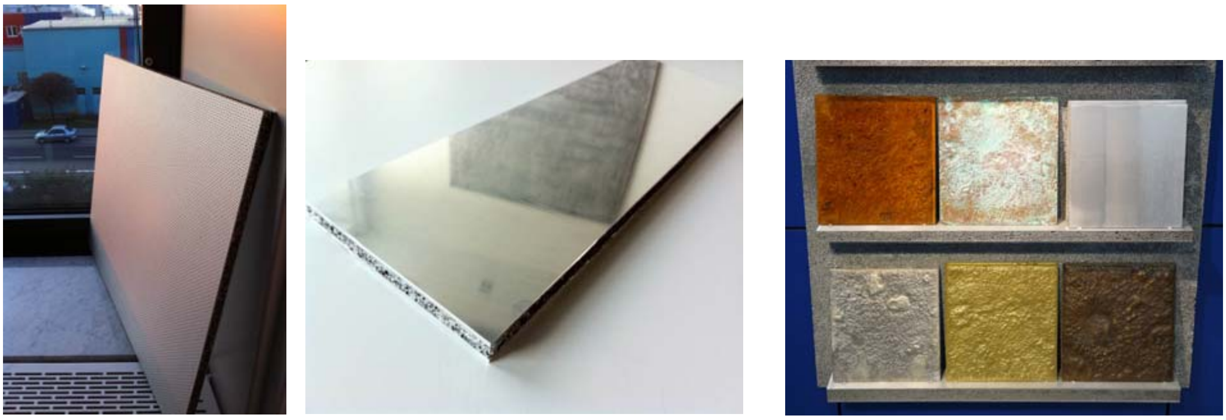


Figure 8. (a,b) AFS architectural plates with (a) dull anodized [18] and structured and (b) shiny polished surfaces, (c) AFS with cor-ten steel, copper oxidized, natural polished, natural amorphous, brass, bronze appearing surface manufactured by coating with a mixture of metal powders and epoxy resin.

The staircase of an up-market residential building in Geneva has been equipped with stair rails consisting of a vertically arranged AFS panel to which the actual handrail was adhesively bonded, see Figure 9. The AFS sheets were left open on the sides so that the foamy nature of the plates is visible. This was the aesthetic motivation for using AFS, another one was its inflammability and robustness.

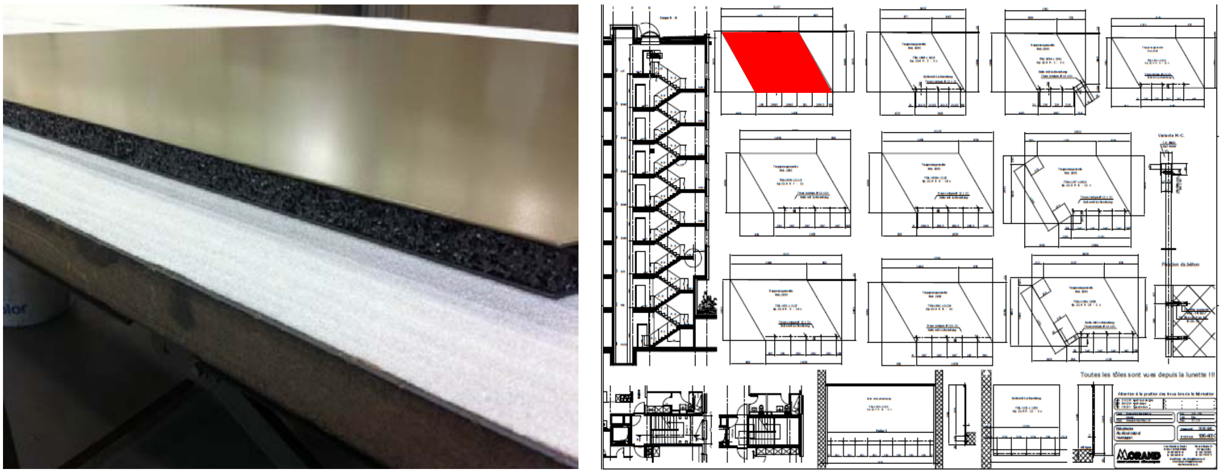


Figure 9. (a) AFS panel used for the base of a stair rail prior to assembly. (b) Drawing of a staircase in a residential building in Geneva containing AFS-supported stair rails. One such element is highlighted in red. In total, 130 AFS segments, each 2.6 m^2 large, were used.

3.5. 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 Figure 10a,b. Use of metal foam for armour has been suggested before for various configurations [19] 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.

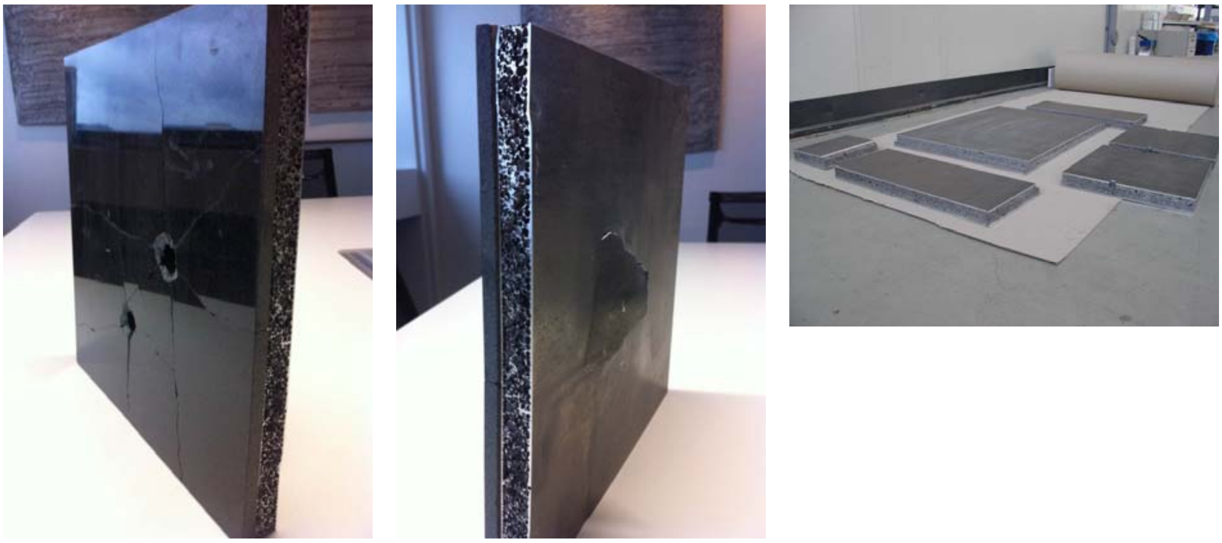


Figure 10. (a,b) Composite of an AFS panel with a polished granite front plate hit by a bullet. The AFS had 1.8 mm face sheets and a 20 mm foam core, while the granite plate was 8 mm thick. (c) Protection for high-speed turning machine built for Kurt Staiger Werkzeugmaschinen GmbH (AFS plates before assembly are shown, size of assembled box is $900 \times 555 \times 755$ mm^3).

Another, less militaristic application is a protective housing for a high-speed turning machine. In such machines parts as heavy as 1.5 kg can loosen and fly away with velocities up to 300 km/h. An AFS casing provides reliable protection in such cases. 4 pieces were built for the German company Kurt Staiger Werkzeugmaschinen GmbH [20], see Figure 10c.

4. Summary and outlook

Aluminium foam technology 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 square metres annually. Experience in the past has shown that without a 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 that have a negative effect on the entire AFS can be avoided. What has remained very much the same is the cost of the product. Strategies to bring costs down include combining various process steps into fewer integrated steps, e.g. to combine powder pressing and rolling as suggested in Ref. 9. Such integrated technologies have been found to be difficult to control and sometimes to have a negative impact on foam quality but still they are the right way to go.

Finally, the search for applications has to focus more on finding the unique selling points of AFS, i.e. as many as possible of the properties mentioned above should be combined in a given application, thus representing multi-functionality.

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