Aluminium Foam Sandwich Panels: Metallurgy, Manufacture and Applications

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ABSTRACT

Sandwich panels consisting of a highly porous aluminium foam core and aluminium-based face sheets are manufactured by roll-bonding aluminium alloy sheets to a densified mixture of metal powders – usually Al-Si or Al-Si-Cu alloys with 6-8% Si and 3-10% Cu – and titanium hydride, and foaming the resulting three-layer structure by a thermal treatment. We review the various processing steps of aluminium foam sandwich (AFS) and the metallurgical processes during foaming. Two ways to treat AFS after foaming are presented, namely forging and age-hardening. Some current and potential applications are described which allows to assess the market potential of AFS.

INTRODUCTION

Metal foam can be produced in a variety of shapes ranging from simple flat products to almost arbitrarily shaped components [1]. Depending on the manufacturing process used, foamed parts exhibit closed outer skins when they have been expanded inside a mould or – in cases the foams have to been cut to size – show partially open pores. The natural skins delimiting foam components increase compression strengths significantly [2], but may be too thin to effectively seal the foam or to provide enough mechanical stability. A proper sandwich design based on dense face sheets can optimise compressional, tensional, torsional or flexural properties much more efficiently [3,4].

The benefit of using sandwich panels becomes clear from Figure 1. An ordinary dense aluminium sheet has a stiffness S given by its thickness *d* and Young's modulus *E*: $S \propto E \times d^3$. Expanding this sheet to a height ηd will not change its mass but Young's modulus will go down to $1/\eta^2$, since $E \propto d^{-2}$, according to experiments [3]. Therefore, *S* is proportional to the expansion factor η. Thus, the stiffness-to-mass ratio of a foam is higher than that of the corresponding dense material which is a reason why foams are good materials for lightweight construction. This comparison, however, is misleading since using simple sheets is the worst thing one can do to optimise stiffness. An optimisation of the mass distribution of a plane sheet at constant mass will rather lead to structures such as the waffle plate shown in Figure 1 which has a much higher stiffness. On the other hand, the bare foam can also be improved by combining it with face sheets and a more meaningful comparison is between optimised structures such as honeycombs or waffle plates on the one hand and foam core sandwich panels on the other. This time the engineered regular structures on the left are stiffer than the irregular foams on the right [3].

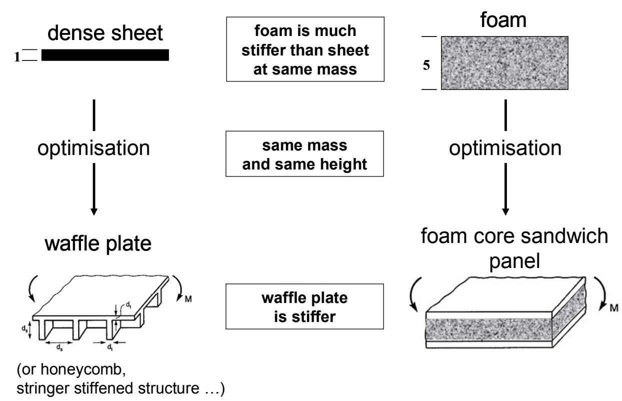


Figure 1. Optimisation of sheets and foams.

In practice, materials selection is not exclusively guided by stiffness arguments. Other aspects are also important such as, 1) ability to produce 3D shapes, 2) costs, 3) elastic limit, 4) failure mode, 5) damage tolerance, 6) available joining technologies, 7) damping behaviour, and other properties. Considering all these aspects one has found real applications for AFS. Automotive industry first picked up the technology when the German car maker Karmann presented a concept car based on AFS in 1996 [5]. At present more applications are emerging, see the following.

TECHNOLOGY

Various technologies have been proposed for making sandwich panels combining aluminium foam and metallic sheets. The most obvious approach is by adhesive bonding. A foam panel – either sliced from a larger block or foamed as flat product in a mould – is glued to two sheets. The properties of the resulting sandwich panel are then given by the interplay of foam, sheet and adhesive and, depending on the parameters chosen, a variety of failure modes are observed [3]. While the adhesive can add valuable properties – e.g. a high damping capacity – usually the problems associated with the glue – high costs, difficult recycling – provide a motivation for different types of bonding. Another way to manufacture AFS was developed at the Fraunhofer-Institute in 1992 [6]. A three-layer composite of a foamable aluminium alloy – containing TiH_2 as a blowing agent – and two face sheets on both sides (usually Al alloy, but steel and titanium have also been used) is made by extrusion or powder rolling and various subsequent rolling operations, after which the core layer of the panel is expanded by heating to the foaming temperature. By shaping the precursor prior to foaming a 3D shape can be produced, see Figure 2.

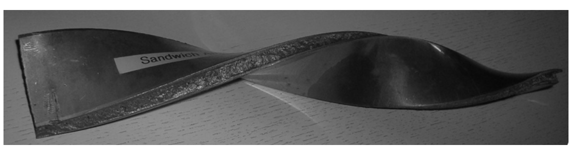


Figure 2. 3D-shaped AFS.

FOAMING PROCESS

Face sheet and foam core have to be made of alloys with different melting points since foaming takes place in the semi-solid or liquid state. At these temperatures the face sheet must not melt. In early foaming practice furnaces were heated to temperatures well above the melting point of the foamable material (e.g. 750°C) to ensure a rapid temperature increase in the material after it had been placed inside the furnace. The corresponding temperature course is shown in Figure 3. As face sheets and foamable core are in close contact and the heat conductivity within the two alloys is high, temperature is approximately the same throughout the material. The material with the lower melting temperature (the foam) therefore damps the increase in temperature during melting and therefore cools the face sheets as long as it is still semi-solid. After total melting temperature rises rapidly and the face sheets start to melt unless the sample is taken out of the furnace for cooling [7]. The solidification temperature of the face sheets T_S therefore has to be above the liquidification temperature T_L of the foam. This restricts the number of usable alloy combinations. Early choices of materials usually were pure aluminium or 3003 alloy (AlMn1) for the face sheets and near-eutectic Al-Si alloys for the foam.

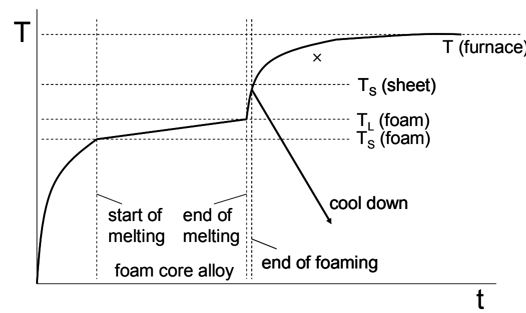


Figure 3. Temperature course of AFS foaming in an unregulated furnace.

The situation is more favourable when the heating process is regulated as it is in modern industrial processes [8]. Here, the foamable material is heated up to an end temperature as quick as possible, after which the temperature is kept constant. This offers the possibility to create the foam just above the solidification temperature of the foam and chose face sheets from alloys which melt just above this temperature, see Figure 4**.**

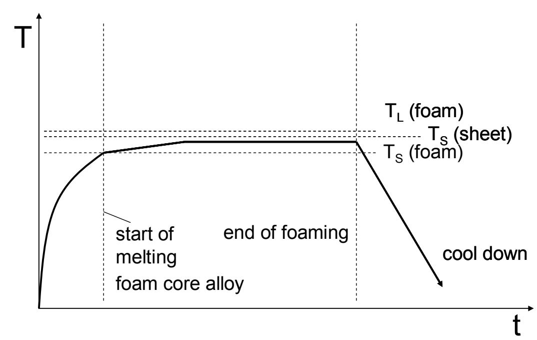


Figure 4. AFS foaming in a regulated furnace.

In this way a wider range of alloy combinations can be processed. Three groups of face sheets are being used:

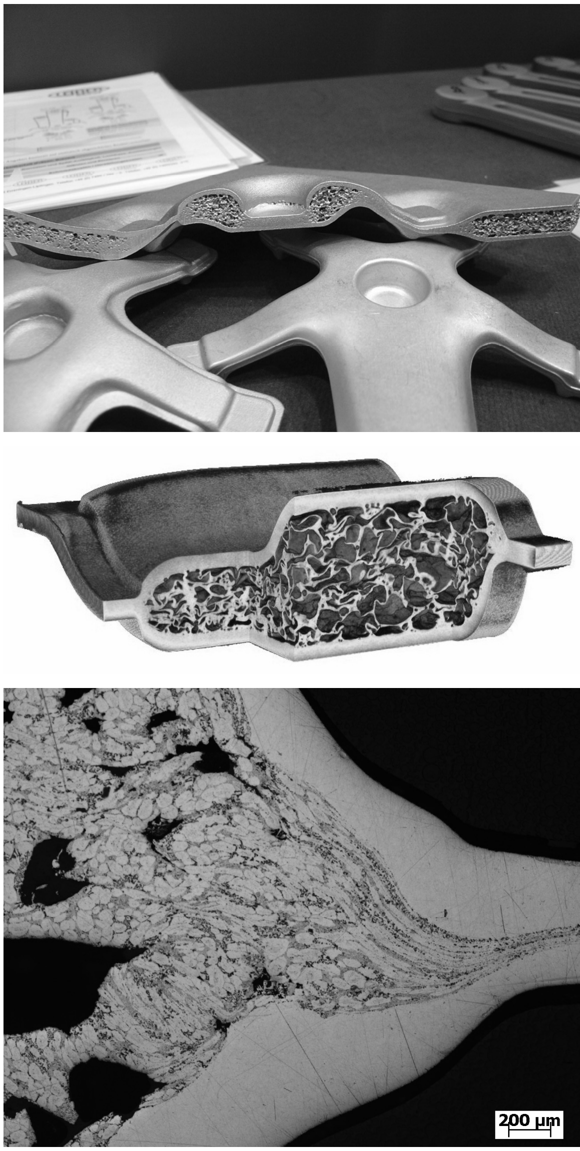
- Non heat treatable 3000 alloys, mainly 3103 (AlMn1)
- Non heat treatable 5000 alloys: 5083 (AlMg4.5Mn), 5754 (AlMg3) or 5005 (AlMg1)
- Heat treatable 6000 alloys: 6016, 6060 or 6082 (Al-Mg-Si system)

For the foam core two groups of alloys based on the Al-Si system have been developed and tested. Currently the alloy AlSi6Cux ($x \approx 3 \ldots 7$) is preferred for its low solidification temperature and very good foaming behaviour [2].

In all cases the foamable core contains TiH_2 in the usual contents, see e.g. Ref. 9, acting as a blowing agent. Blowing agents are pre-treated to tailor the temperature of gas release according to the principles outlined in Ref. 10. Foaming larger panels is a real challenge since a uniform temperature profile has to be maintained on an area of up to 3 m^2. Deviations can lead to foam collapse or damage.

PROCESSING OF FOAMED AFS PANELS

Foaming of the 3-layer composites leads to flat AFS panels unless the panels have been shaped prior to foaming. Due to differences in temperature and heterogeneities of the starting material panel thickness is usually not uniform and the AFS panels have to be calibrated in a hot press. Two further processing steps are worth mentioning here since they provide unique opportunities: forging and age-hardening of AFS.



(a) (b) (c)

Figure 5. Forged AFS, (a) part and section, (b) tomogram of interior (courtesy F. García-Moreno), (c) microstructure of densified rim.

Forging of AFS

Although AFS technology allows one to manufacture 3D-shaped sandwich panels, these have a nearly constant cross sections and open edges. Forging provides a unique opportunity to manufacture more complex-shaped parts which are closed while maintaining a porous core. For this, AFS panels are cut to a suitable size and are forged in a die. Figure 5a shows one such part.

Although one might expect that forging largely destroys the foam structure, the tomographic image, see Figure 5b, shows that this is not the case. Figure 5c demonstrates the benefit of the method, the very good densification at the margin of the part which seals off the foam core and facilitates fixture of the component in engineering systems.

Age hardening of AFS

Whenever AFS contains heat treatable alloys, age hardening can be considered. Age hardening the foamed core has been studied [11] but is difficult to carry out in the AFS process chain. Age hardening of the face sheets has been shown to improve the mechanical properties of AFS. Since AFS cannot be water-quenched without the danger of warping or failure, a T5 treatment of 6082 face sheets has been studied which comprises natural cooling after foaming and a subsequent artificial ageing step [12]. T5 was shown to yield a hardness value between the value of the 'as foamed' states and the full T6 hardness.

APPLICATIONS

Telescope lifting system

Teupen (Germany) has developed a novel concept for the support structure of a telescope arm lifting a working platform. The goal was to increase the working height from 20 m to 25 m, the horizontal outreach to 11 m, while keeping the total vehicle weight below 3500 kg, a vehicle category for which European drivers just need the 'Euro B' driver's licence which is an advantage for the operating company. The structure consists of 6 AFS panels and a number of Al sheets which are welded together by MIG and TIG. An insert for the axis is glued into a drilled hole. The structure, see Figure 6, has been tested under multiaxial cyclic loads (100 kN vertical, 14 kN horizontal) and passed the requirement of 40000 cycles without failure.

Figure 6. Vehicle with 'EURO B25T' lifting arm support.

Alimex plates

Alimex (Germany) has added an AFS sandwich panel to its product line of high-precision and high-stiffness aluminium plates (cast and rolled). The AFS plates are more than 50% lighter than their corresponding dense counterparts and merely 8% less stiff. Costs are higher but the spectrum of properties, including good weldability of the 6 mm thick alloy 5083 face sheets, inflammability, insulation properties etc., make these plates good candidates for a applications, e.g. in metrology or machine engineering.

Ariane 5 rocket adaptor

The European ‘Ariane 5’ rocket uses two cone-shaped adaptors which support the payload. At present they are made of aluminium honeycombs and have to be processed under high costs. The objective of replacing these cones by a cheaper and easier to handle AFS-based version was met by welding together 12 curved AFS (alloy 6060 face sheets) segments by TIG welding [13]. The resulting cone, see Figure 7, is almost 4 m wide at the base and weighs 180 kg. In tests with up to 100 kN load both in the normal and the shear plane the prototype showed sufficient strength but a stiffness which was still 10% too low. The next prototype will be built accordingly with higher stiffness.

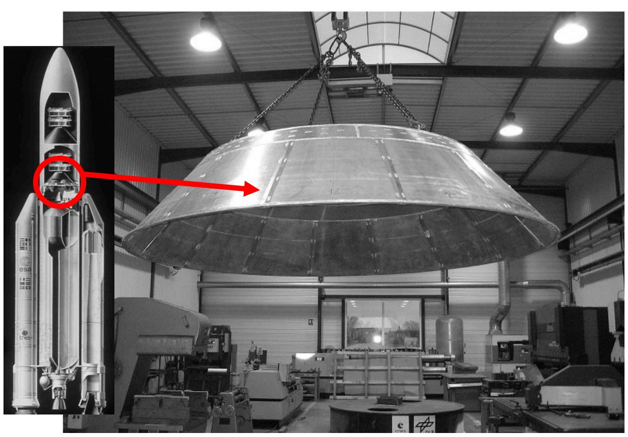


Figure 7. Ariane 5 rocket cone prototype made of AFS.

Bicycle crank arm

AFS forging has found a first prototypical application with a crank arm for racing bicycles. Conventional parts are made of forged 6082 alloys. The lightest parts on the market weigh slightly more than 300 g. The forged AFS replacement of the crank arm – see Figure 5 – weighs 222 g, i.e. 30% less. This is a big achievement since the lightest products on the market currently differ by some tens of grams only. As AFS forging technology is cost effective and the design can still be further optimised, a potential high volume market can be anticipated.

SUMMARY

AFS technology allows one to manufacture both flat and curved Al foam core sandwich panels and to shape them to more complex closed components by forging. Improved foaming technology has widened the range of accessible alloys for both the skins and the core. Heat treatment to T5 improves the strength of 6XXX alloy face sheets without the need for quenching. The number of serial applications is still small but promising prototypes have been developed recently. The availability of AFS through various companies [14-16] will facilitate the development of applications. Currently, manufacturing technology is being developed with the prime objective to reduce costs by making processing routes shorter and to ensure a more constant quality. Some novel approaches for making AFS precursor such as powder rolling have been proposed [17].

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