



TECHNICAL ARTICLE

Aluminum Foam Sandwiches: A Lighter Future for Car Bodies

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An aluminum foam sandwich (AFS) is a lightweight material that has great potential for applications in the automotive industry. In this work, the production routes of metal foams and metal foam sandwiches are reviewed. We compare the mechanical properties of AFS, such as high mass-specific bending stiffness, compressive strength and crash-absorption capacity, with other materials such as steel, aluminum alloys, or fiber composites and place them in a cost/weight comparison. Additional functional properties such as high electromagnetic damping, increased sound absorption, and improved fire resistance underline its multi-functional character. Furthermore, possible joining techniques and parts of AFS for modern car bodies, such as the battery box, are discussed.

INTRODUCTION

In order to support the transition to hydrogen and electric mobility in road transportation and to exploit new potentials for lightweight structural applications, constant innovation and further development in the field of novel materials and engineering solutions are required. The advent of new material and process routes secures an important share of added value in this sector of future technology. Lightweight materials such as aluminum alloys have been developed, optimized, and applied for a long time.¹ Therefore, the potential for improvement is small and for now limited, e.g., to the development of new thermal treatments or to alternative light and strong alloys such as Al-Li or Al-Sc,² but the cost of lithium and scandium and the almost monopolized supply (66% of all Sc comes from China, 26% from Russia) have so far prevented a more widespread use of such alloys.

Nevertheless, the use of a lightweight metal such as aluminum, which makes it possible to optimize mass-specific material properties and reduce weight where it is not needed, has become inevitable. Workpiece optimization by computer assisted

design and computerized numerical control machining are state of the art. An effective way to greatly improve already existing materials is to shape them as cellular structures by applying manufacturing techniques ranging from welding and brazing to modern additive manufacturing (AM) methods.³ Although the latter are spreading rapidly, they are still slow and expensive compared to traditional production methods such as casting, extrusion, or forging. Luckily, cellular metals can be produced in a more cost-effective way, namely by foaming an alloy. It is expected that many components in cars, ships, or trains can be made lighter without compromising or even improving their function by using tailored metallic foam components.⁴ The development of new foamable alloys and corresponding foaming technologies allows designers to consider new concepts for the automotive and other transportation sectors.^{5–8} Although the production and product control of foamed metallic structures is still not as precise and flexible as, for example, AM techniques, it is hoped that metal foams will follow their polymer counterparts which have found widespread application.

Foams can be notably improved by combining them with dense material. The most well-known combination is that of a (metal) foam and two metal face sheets, and the result is a (pure metallic) foam sandwich panel. An aluminum foam sandwich

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(AFS) is built up in three layers: two solid, force-absorbing surface aluminum alloy layers are kept at a distance by a lightweight metallic foam core. The result is very lightweight, flexurally rigid components or semi-finished products that combine the properties of standard sandwich structures in general with those of metal foam, leading to exceptional specific properties compared to other materials, such as a great energy absorption capacity in the event of an impact, high recyclability compared to composite materials, high temperature resistance, and improved vibration damping.

In this work, the advances in manufacturing technology of metallic foam sandwiches, and especially of AFS, are briefly reviewed, and their promising application opportunities in the automotive industry discussed.

METALLIC FOAMS

Metallic foams have been known for decades,⁹ but their industrial breakthrough is yet to come. They have been proposed for many different applications and industrial sectors, including automotive, ship building, rail transportation, aviation, civil engineering, and military.^{5,6,8,10-13} The current work concentrates on closed-cell foam structures, as open-cell structures (sponges) are mainly used for functional purposes, such as filters, catalysts, electrodes, or medical applications,^{8,13} and less for structural applications. A simple classification diagram of cellular metallic materials can be found in a review by Garcia-Moreno.⁸ Metals foamed following the liquid metal route can be produced industrially in high volumes and cost-efficiently by the gas injection method¹⁴ or the Alporas method.^{15,16} Especially the latter is currently applied by various Asian companies, mainly to produce foam panels for architectural applications or mechanical engineering, but also for sound absorption, damping, or temperature control (cooling).¹⁷ Although such foams have their (probably restricted) market, pure foam plates or blocks are in general hard to integrate directly in structural applications, as the post-processing and joining techniques required are difficult to apply. A sandwich configuration promises easier integration into systems besides improved properties.

METAL FOAM SANDWICH

Bare foams perform poorly in tension and break easily under tensile or bending load. In contrast, foams with attached face sheets in a sandwich configuration offer advantages; e.g., they can bear tensile and bending loads.^{18,19} Several procedures can be applied to obtain foam sandwich panels. Firstly, a flat foam can be produced by following any of the existing metallic foam production routes described in the literature²⁰ or by slicing larger blocks of foam, after which a large variety of face sheets is adhesively bonded to the foam.²¹ This

technique has the advantage that almost any material combination is imaginable. However, as the purely metallic character of the composite is lost, the material shows weaknesses with regard to mechanical behavior, heat resistance/flammability, and/or recycling. Secondly, another approach consists of placing flat sheets of foamable precursor, i.e., powder metallurgically-generated precursor material, that can be converted to foam, between two face sheets. The entire batch is then heated, whereby the core expands and joints with the face sheets. With this technique, steel–aluminum and aluminum–foam sandwiches can be produced.²² However, achieving a strong metallurgical bonding between the face sheets and the foam core is a challenge, as two strongly oxidized surfaces must fuse. Bonding can be achieved by rolling the three layers at a certain temperature before foaming, thus creating a metallic bonding. Thirdly, a more advanced production method has been developed by the Pohltec Metalfoam company and consists of compacting and hot-rolling an aluminum container filled with a foamable powder blend, i.e., aluminum powders, powdered alloying elements, and a small fraction of the blowing agent, titanium hydride, thus achieving a metallurgical connection between a foamable core and the face sheets during precursor production in just one step (see Fig. 1). The AFS panels are produced by heating the composite in an infrared furnace, during which the core expands while the face sheets remain solid. The resulting foam panel is then levelled and calibrated in thickness in a press at $\sim 500^{\circ}\text{C}$ to ensure flatness.

ALUMINUM FOAM SANDWICH

AFS is characterized by a metallurgical bonding between the face sheets and the foam core. It can be produced in total thicknesses down to 8 mm (with 0.75-mm face sheet thickness) and up to 60 mm. Exemplary parts of AFS in various sizes and surface finishing states are shown in Fig. 2, and a description of the commercially available parts can be found in the internet.²³ Because entire panels are composed of one material class only (Al alloys), standard aluminum processing techniques, such as welding, bending, milling, laser cutting, or grinding, can be applied. Moreover, easy maintenance or repair of damaged parts is possible. Some specifications of already commercially available AFS parts are listed in Table I.²³

Sandwich panels in general have a high mass-specific bending stiffness. Compared to polymeric foams, AFS exhibits a remarkable compression strength, namely up to 10 times that of polyurethane foam.²⁴ An almost constant compression strength plateau over a large deformation range leads to a very good energy absorption performance, as demonstrated for quasi-static compression experiments perpendicular to the face sheets of the AFS sample of 9 mm thickness, 0.75 mm EN AW-6082

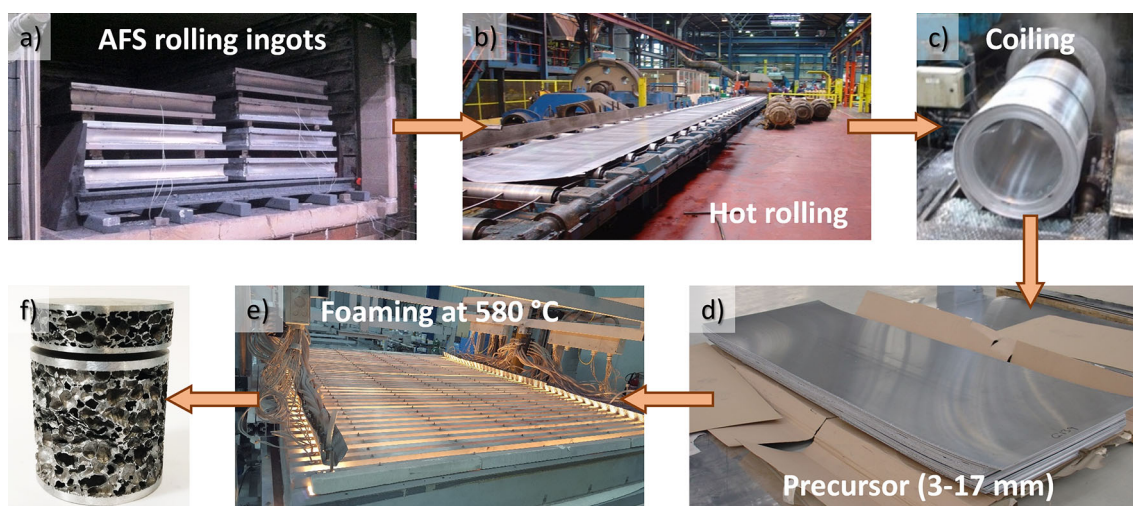


Fig. 1. The production process of AFS in various steps: the powder-filled rolling ingots (a) are hot-rolled (b), coiled (c) to three-layer precursors of various thickness (d), and then foamed in an IR lamp furnace at elevated temperatures (e) to AFS of different thicknesses (f). Adapted with permission.⁷ Copyright 2019, Springer Nature.

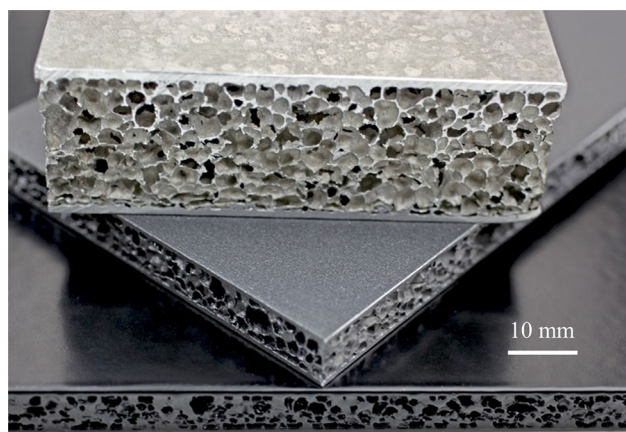


Fig. 2. AFS samples in various sizes and surface finishing states. Reproduced under the terms of the CC-BY license.²³ Copyright 2015, pohltec metalfom.

Table I. Commercially available AFS specifications

Property	Value
Maximum AFS sizes	2500 mm × 1100 mm
Sandwich thickness	8–60 mm
Foam core	AlSi8Mg4 alloy
Face sheets	0.75–6 mm (EN AW-6082 and others)

face sheets, and a foam core density of $0.38 \pm 0.03 \text{ g/cm}^3$ shown in Fig. 3, and compared there to its solid counterpart of the same mass. Allowing for straining to a given stress level leads to a much higher energy absorption by the foam. For

dynamic compression, a further contribution to energy absorption is expected from the additional effect of the air enclosed in the cells.²⁵

In addition to these compression characteristics of metal foam, AFS also shows a high electromagnetic damping up to 118 dB,²⁶ an increased sound damping, especially at frequencies < 400 Hz (up to 4 times higher than solid aluminum), and an improved fire resistance due to the heat dissipation capability of the cellular structure (up to 25 min longer than solid aluminum at 950°C).²⁷ This combination of properties makes AFS a promising multi-functional material for the automotive sector.

The current challenges for the use of AFS in the automotive industry lie in improving the manufacturing process or parts of the production chain in order to further improve the properties of the finished sandwiches and make the process more reliable. In addition, an improvement of the production volume adapted to the demand of the automotive industry must be ensured by scaling up the actual production facilities available. Last, but not least, the reduction of actual production costs could be decisive for a breakthrough in applications. Before showing possible applications of AFS in modern cars, some well-known materials for the body-in-white are reviewed.

PRESENT MATERIAL UNIVERSE OF BODY-IN-WHITE

At first glance, the composition of modern body-in-white (BIW) is relatively simple. In compact cars, the BIW is dominated by steel and only small volumes of aluminum are used. In medium-size cars, aluminum is more prominent and also becoming more popular, whereas in luxury or sports cars, a mix of aluminum, steel, and carbon or glass fiber-reinforced polymers (C/GFRP) is becoming

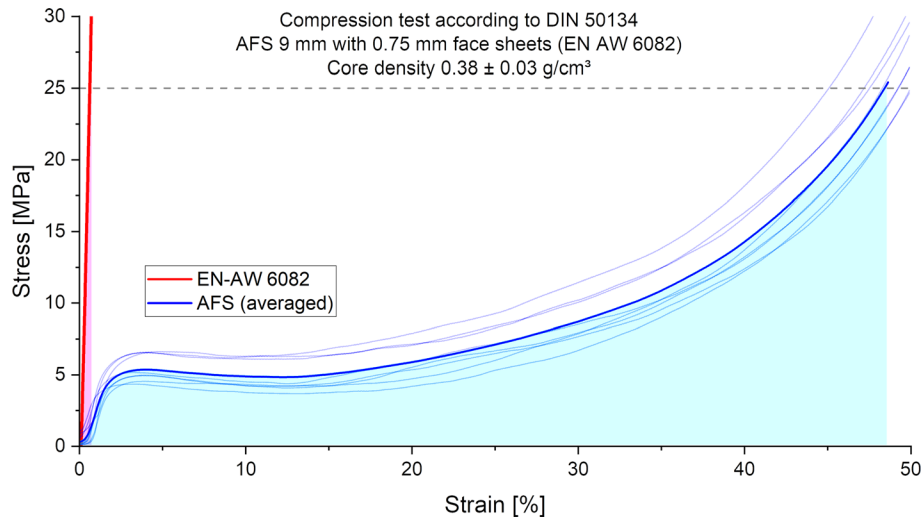


Fig. 3. Quasi-static compression curves of AFS samples of 9 mm thickness, 0.75 mm EN AW-6082 face sheet, and a core density of $0.38 \pm 0.03 \text{ g/cm}^3$. Load direction perpendicular to face sheets. The area highlighted in cyan represents the integral of the averaged stress-strain curve of 8 samples and is equal to the energy absorbed by AFS up to 48% strain corresponding to a stress of 25 MPa. Solid aluminum strained to 25 MPa (red line) absorbs much less energy (see light red area) (Color figure online).

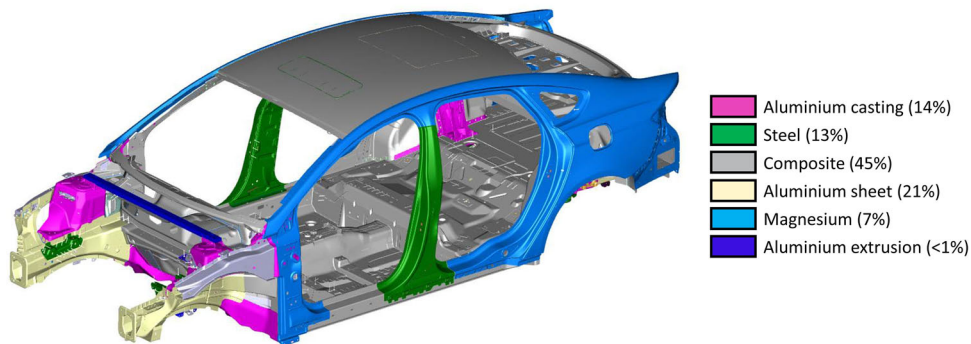


Fig. 4. Mixed-material lightweight vehicle, Mach-II BIW. Floor and roof components employ carbon composites in lightweight BIW. Reproduced under the terms of the CC-BY license.^{28,32} Copyright 2014, T. Skszek.

arguable. The focus has moved towards a mix of the materials, as the key formula to produce a safe, stable, and light car,²⁸ as shown in Fig. 4. In the so-called safety cell, the passenger cabin, ultra-high-strength steel is applied to minimize crash intrusion combined with the weight-saving properties of magnesium. Die-cast aluminum for maximum rigidity is preferably implemented in the front bumper strut consoles and rear axle suspensions. Aluminum sheets, or CFRP in sports cars, are extensively used for the car body to reduce mass.^{29–31} Sandwich materials including paper honeycombs or polymer foams are used only in the interior, e.g., at the rear shelf.

The development of steel types accelerated at the beginning of the last century, with high-speed steel (HSS), and continued with ultra-high-strength steel (UHSS), hot-formed UHSS, and UHSS with tailored properties. The future of steels lies in steel

sandwiches with UHSS (e.g., with corrugated sheets as cores) with better ductility and a further increase of weight-specific strength. For aluminum, the history looks similar. Initially, steel parts were substituted by aluminum parts, later the design was varied, and high-strength alloys were developed. The future also lies in stronger alloys with tailored properties, using new hot-forming and casting technologies.³³ In 2015, Ford changed the material of the body of the F-150 from steel to aluminum to save about 300 kg of weight. However, even with this change, the net aluminum content of the F-150 is only approximately 25%.³⁴ Therefore, although steel might lose a few percent of the metal market in the automotive sector, it will still dominate BIWs for the next decades.

Looking at more exotic materials, e.g., CFRP, consumption in the automotive industry was 37,130 t in 2018.³⁵ Taking into account that almost

95 million light vehicles were sold in 2018 globally,³⁶ only 0.39 kg of CFRP were used per vehicle. In 2025, a growth rate for CFRP use in the automotive industry of 20% per year is expected. By taking an estimated 110 million light vehicles sold per year, the CFRP/vehicle would rise to ~ 1 kg in comparison to an expected 187 kg Al/vehicle.³⁷ This development will not bring CFRP in the position to play a significant role for fleet vehicle weight-saving in the near future.

Another possible composite material is metal matrix composites (MMCs). Here, fibers or particles, typically a ceramic, are distributed in a metallic matrix such as copper, aluminum or steel. The composite usually gives them higher strength, stiffness, and ductility, as well as high wear resistance. In the automotive industry, they are now used in brake drums, drive shafts, and cylinder liners.^{38,39} For magnesium, the weight percentage in standard baseline vehicles is negligible and can increase up to 0.2% in advanced lightweight designs using existing commercially available materials and production processes.³² Consequently, magnesium remains an outsider. The same role is played by additively manufactured parts, but their production is expected to rise between 25% and 40% in the future depending on different sources.⁴⁰ Steel and its varieties will most likely remain the dominant player in the BIW. Despite that, lightweight designs and the exploitation of all related advantages are the most important challenges to master.

To implement lightweight materials in new BIWs, a simple, but clear, diagram, was presented by Mattheus in 2010.⁴¹ It shows that most original equipment manufacturers in the automotive industry declare a budget of around 10 € to invest to save 1 kg of mass. Currently, only steel and aluminum are the candidates reaching this target. CFRP is very promising and shows an impressive weight-saving potential; however, it is still too expensive to be used in higher volumes, at least not for compact or medium-sized cars. Beside the weight versus cost, some other requirements need to be fulfilled to make the material attractive, e.g., standard production techniques or further functional advantages. Neither points are easy to be accomplished by CFRP. In that case, additive manufacturing becomes more arguable, as functionalities can be

easily implemented, but to a high cost. In the following, the potential of AFS is discussed under these points of view.

AFS FOR MODERN BODY-IN-WHITE

Based on the lightweight corridor of 10 €/kg, the potential of AFS in modern BIW is discussed in the following. With standard production techniques, AFS can be handled almost like solid aluminum as no non-metallic component is involved. Examples of post-production techniques are laser and waterjet cutting, edging, punching, milling, grinding, cutting, rolling, standard joining techniques (are explained in detail later), powder coating, and welding. In comparison to all fiber composites, no special safety requirements need to be satisfied during production as, e.g., an exhaust ventilation system.

AFS is compared in Table II to other materials used in the automotive sector: dual phase (DP) steel, aluminum, MMC, and CFRP. It should be noted that, for this comparison, we use default values for each class of material, although there are large variations within each class due to the variety of alloys or compositions. The density of AFS is almost one order of magnitude lower than that of steel. This is the reason why the properties have always to be related to the weight. Especially, the tensile strength of steel and aluminum can vary considerably. In the case of bending loads, where the tensile strength of the foam core in AFS is not of great importance, the comparison can give a feeling of how AFS performs. The cost per weight for AFS is set to 10 €/kg, which is estimated once a mass production line is in operation.

To find materials for a special purpose or application, material selection diagrams designed by Ashby are useful.⁴³ One such diagram restricted to the materials listed in Table II and displaying Young's modulus versus density can be found in Fig. 5. The lines in the diagram show the best stiffness-to-weight ratio to design a light and stiff rod (in blue), beam (in red), and plate (in green). For a light and stiff rod, CFRP would be the best choice, as the Young's modulus, E , is inversely proportional to the material density, ρ . Because a plate's bending stiffness scales as its thickness cubed, the best material for a stiff and light plate is determined by

Table II. Standard values of materials used for BIWs in comparison to AFS; several values extracted from Ref. 42

	DP steel	Aluminum	MMC	CFRP	AFS
Tensile strength in MPa	700	310	400	1550	200
Young's modulus in GPa	207	70	102	138	21
Density in g/cm ³	7.87	2.7	2.7	1.55	0.8
Costs in €/kg	1	4	9	15	10 (series)

the cube root of Young's modulus divided by the density, $E^{1/3}/\rho$. Therefore, the most convenient shape of a metal foam is a plate by which density plays a more significant role than Young's modulus, or, even better, optimized as a sandwich plate, where the bulk face sheets support the highest loads, making AFS competitive with CFRP.

Designing a simple plate of 2000 mm × 1000 mm size that exhibits the same bending stiffness for the four materials shows that 8-mm AFS is as rigid as 4.7-mm steel, 6.8-mm aluminum, and 5.4-mm CFRP, as presented in Table III. Furthermore, it is found that, by using AFS, 83% of weight can be saved in comparison to steel, and only 0.9 €/kg need to be invested, which is superior to CFRP (3.1 €/kg) and Al (2 €/kg).

Even though AFS reaches the lightweight corridor, it is still challenging to implement the material in traditional BIWs. AFS consists not only of two face sheets and a highly porous core (which is in most cases totally new for automotive constructors) but also of a minimum panel thickness of 8 mm to unleash its full potential, and therefore by far thicker than usual metal sheets (0.5–2 mm). This fact makes a structural lightweight design and a substitute exchange one-to-one of already existing components almost impossible. However, if AFS is considered in an early stage of the BIW design, and ascribed even further functional advantages, the new material becomes indeed interesting. Such a

possible application combining most of the unique properties of metal foam is described in the following.

AFS CONCEPT BATTERY BOX

In modern electric cars, the final design of the BIW is still not clear and several concept studies have been discussed, including various materials for lightweight design.²⁸ Without a central engine, the necessity to transmit power from the front to all the wheels and a gear box are no longer needed. Thus, a flat underbody construction is the most efficient concept. Therefore, it seems very likely that the heavy battery compartment is situated in the lower center of the car between the underbody sheet, the passenger compartment floor, and the wheels (see Fig. 6a). This configuration leads to a better driving performance due to a targeted low center of gravity. The electric engines are then placed directly on the wheel axes, or even as direct-drive in-wheel motors.⁴⁴ Hitherto, this “skateboard” design has been used for most of the battery compartment modules, and consists of a multilayer structure of various Al or steel plates fulfilling various requirements and functions (e.g., impact protection, cooling, bracing, fire protection, etc.) and massive vertical struts to increase stiffness. While this is a viable solution, it leads to a considerable increase in the mass of the car.

In contrast to the traditional approach, the AFS concept battery compartment comprises just two panels: an underfloor (final bottom layer to the street) and a floor panel (border to the passenger cabin) (see Fig. 6c). Both are made of AFS and bonded to extruded aluminum alloy sections by punch rivets and automotive adhesives. The space in between is designated for the battery modules. Partial densification of AFS (see Fig. 6b), is carried out to seal the edge elements and to allow a proper connection to the substructure by using standard connection techniques (riveting, gluing, etc.). However, the largest percentage of the AFS is not densified to improve performance. The values in Table III show that, by using AFS, the same bending stiffness can be achieved with 65% less weight compared to solid aluminum, including an increased impact protection.

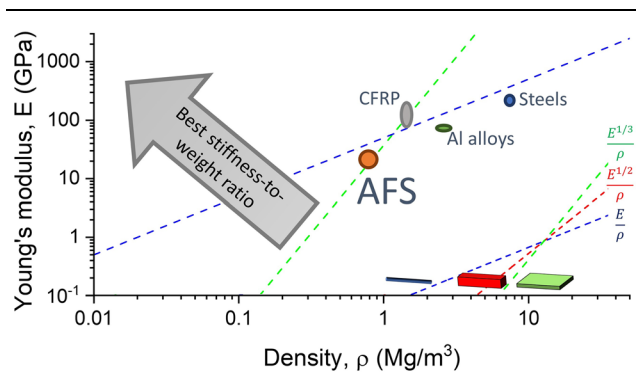


Fig. 5. Material selection diagram comparing AFS, CFRP, Al-MMC, Al-alloy, and steel by their Young's modulus and density according to Ashby.⁴³ The lines indicate the best stiffness-to-weight ratio for a rod (blue), beam (red), or plate (green) (Color figure online).

Table III. Comparison of steel, aluminum, CFRP, and AFS plates of the same bending stiffness in regard to weight reduction and costs/kg saved

	DP steel	Aluminum	CFRP	AFS
Required thickness for same bending stiffness	4.7 mm	6.8 mm	5.4 mm	8 mm
Weight	74.0 kg	36.7 kg	16.7 kg	12.8 kg
Weight reduction		– 37.3 kg	– 57.3 kg	– 61.2 kg
Costs	74 €	147 €	251 €	128 €
Additional costs/kg saved (steel as reference)		2.0 €/kg	3.1 €/kg	0.9 €/kg

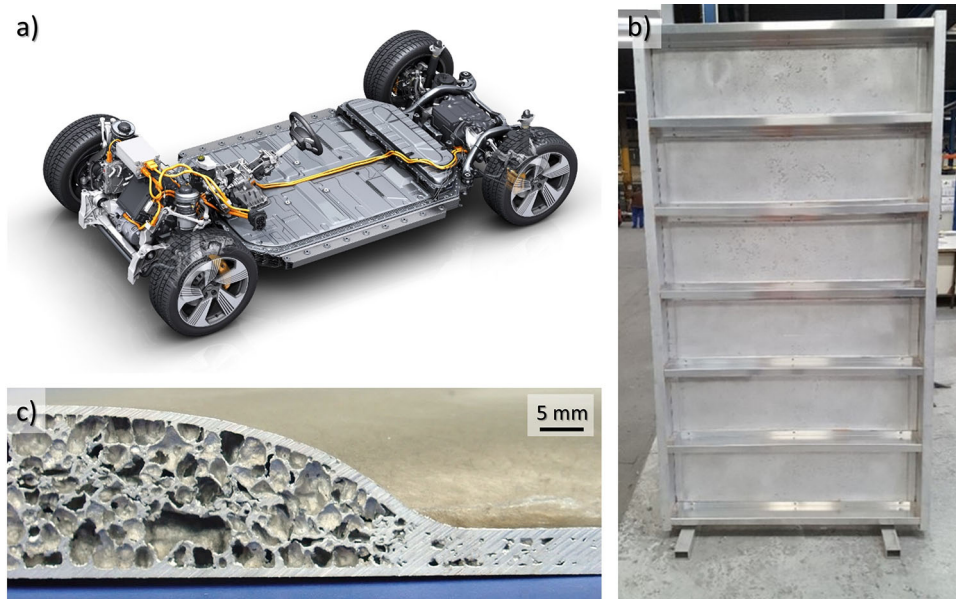


Fig. 6. Battery case concepts for electric vehicles: (a) drivetrain of the Audi e-tron and its design for the location of the battery case. Reproduced with permission.⁴⁵ Copyright 2019, Springer Nature. (b) Module comprising underbody (reverse side) and battery compartments (observed side). Reproduced with permission.⁷ Copyright 2019, Springer Nature. (c) Example of an uncompressed to compressed transition area of AFS to seal the edge and to attach the panel to the underbody of an electric vehicle.

Joining Techniques

As already discussed in the previous section, several connection techniques are feasible without any modification compared to conventional metal sheets: gluing, welding, or AFS as clamped components, etc. Approaches of alternative connection techniques in foamed areas are also under development, and are shown in Fig. 7. Thereby, there is a need to distinguish between pilot hole connections (Fig. 7 and c), versus pilot hole free connections (Fig. 7b), as well as thread inserts (Fig. 7a) or directly connected tools (Fig. 7b). Thermal adhesive bonding boss TSSD[®] (market name EJOT) fastening elements for porous and lightweight constructions can also be used as a direct connector, and also as a thread insert, as shown in Fig. 7c.

Another approach for the connection of the foamed parts is to partially densify some areas of the AFS plate to the initial thickness of the precursor, as already seen in Fig. 6b). Thereby, the solid and massive character of a standard aluminum alloy plate is almost reached and standard connection techniques like punch riveting or the setting of blind rivet nuts are possible (see Fig. 7). Depending on the type of blind rivet nuts used, maximum torque values > 24 Nm (punched and with Allen screws) are possible. The partial densification also has the advantage to close the open cells in the surrounding. This is a prerequisite for any use in a wet environment. Especially in the automotive industry, the closing of the surrounding is also required to be able to cathodic dip-coat the entire BIW for corrosion prevention.

On densified areas of the AFS plate, other joining technologies can also be applied. Depending on the joint requirements, it seems possible to use diffusion bonding or cladding, although neither has yet been tested on AFS. The diffusion welding process is mainly suitable for joining different metals. Normally, the interfacial diffusion requires high temperature (50–80% of the melting temperature), pressure, and sufficient processing time. However, a significant increase in one input (e.g., pressure) can significantly reduce the requirements in another area (temperature or processing time). Plating is the process of laminating a layer onto the base material. This can be achieved by roll bonding, explosion welding, or laser welding. The process adds another new functionality to the resulting metal composite. These functions can include corrosion resistance, wear resistance, electrical conductivity, and thermal conductivity.⁴⁶

Crash/Impact Protection

The protection against any crash or impact is very important in the transportation industry (road, rail, marine, etc.). This is especially important for electric vehicles without the traditional motor block in the front. The EU project “Evolution” investigated AFS as a possible lightweight material, for example, as bumper support to absorb impact energy in case of an accident (see Fig. 8).

Another critical part was perceived in the bottom plate and underbody construction of electric vehicles. The following scenario could be observed in real traffic, causing catastrophic damage to the

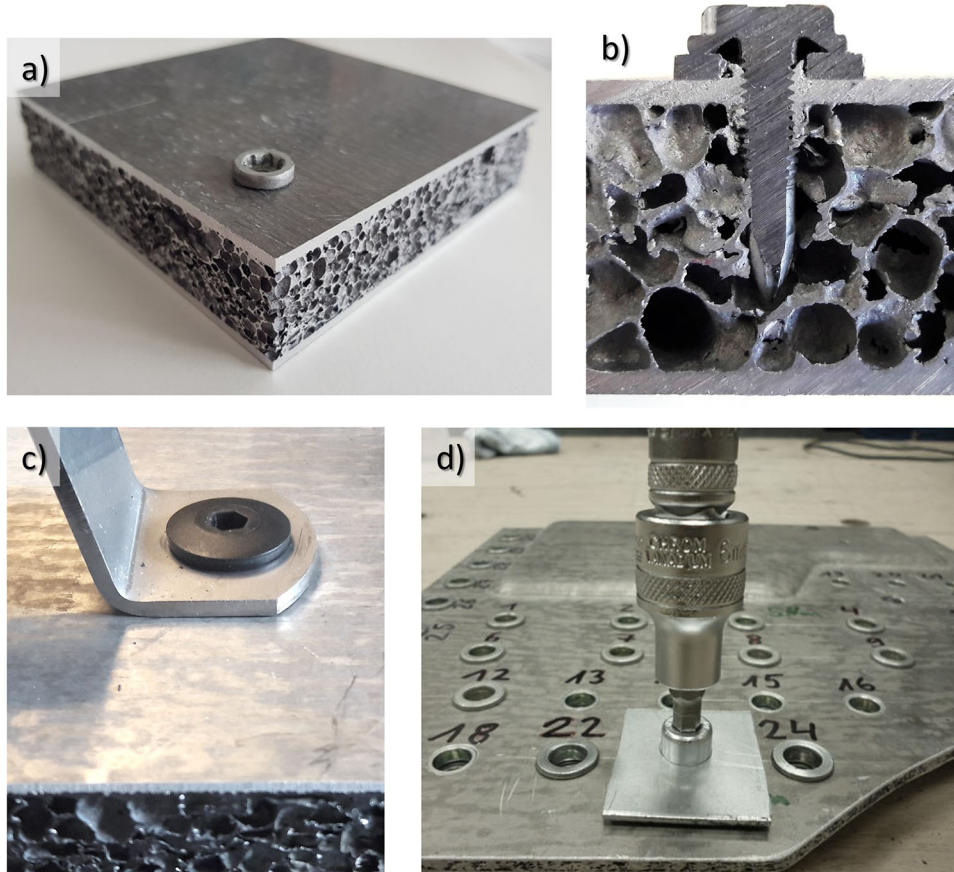


Fig. 7. Possible alternative joining techniques in foamed areas: (a) pilot hole thread insert prototype with inside thread by Stanley Engineered Fastening TUCKER, Gießen; (b) flow drill screws (FDS) without pilot hole by EJOT allowing for 2-kN pull-out force at 1 mm face sheet thickness; (c) firmly bonded TSSD polymer connector with pilot hole by EJOT allowing 2-kN and 2.6-kN pull-out force for 1 mm and 1.5 mm face sheet thicknesses, respectively; (d) torque tests to evaluate the maximum torque value of various blind rivet nuts; punched rivet nuts with Allen screws can resist forces > 24 Nm.

battery modules: A loose tow hitch ball lying on the street lost by a vehicle ahead was flung out by a wheel and shot through the bottom plate, creating an electric short circuit in the battery system and setting the car on fire. The first attempt of car manufacturers to solve this problem was to place a thicker or stronger plate at a distance below the central battery. This, however, again adds considerable mass to the car. A lighter solution against such an impact is the use of AFS and its impact energy absorption capability. To evaluate its performance, a test series was conducted dropping a hitch ball (US standard steel tow hitch system) on the AFS (6.5 mm metal foam core, 2×0.75 mm face sheets) fixed on a frame analogue to the one of a vehicle (see Fig. 9a). The projectile, a tow hitch ball, was dropped from a height of a maximum 10 m. To achieve more realistic conditions, the impact test was also performed under a certain angle of incidence (see Fig. 9b). The weight of the projectile was increased 5 times to 7.5 kg (Fig. 9c) to simulate impact energies at 112 km/h (70 mph).

Under a flat angle of 26° AFS (see Fig. 9d), the deformation on the opposite impact side is small: 4–

6 mm, which is non-critical for the battery modules (max. 25 mm was given by a customer as non-critical). For higher impact loads, cover layers need to be redesigned (stronger or thicker Al-alloy, steel, GFRP, or CFRP). However, even with just a standard EN AW-6082 additional cover of 2 mm thickness on the impact side, catastrophic damage can be prevented with a deformation of ~ 20 mm, as can be observed in Fig. 9e).

Additional to physical deformation tests, a comparative computer-aided engineering (CAE) simulation with the software LS-Dyna was carried out between an all Al alloy solution (Fig. 10a) and an AFS-Al alloy solution (Fig. 10b). For the Al-alloy and the face sheets of AFS, EN AW-6082 was used (Young's modulus 70 GPa, Poisson's ratio 0.34, and density 2.7 g/cm^3). For the AFS foam core, an elastic modulus of 5 GPa, a Poisson's ratio of 0.3–0.5, and a foam density of 0.3 g/cm^3 were used. Both systems were equal in weight and installation space/height. As a comparative value, the force to deform the two systems by 1 mm under a constant quasi-static load was calculated and the results showed that the deformation resistance of the AFS-Al alloy solution

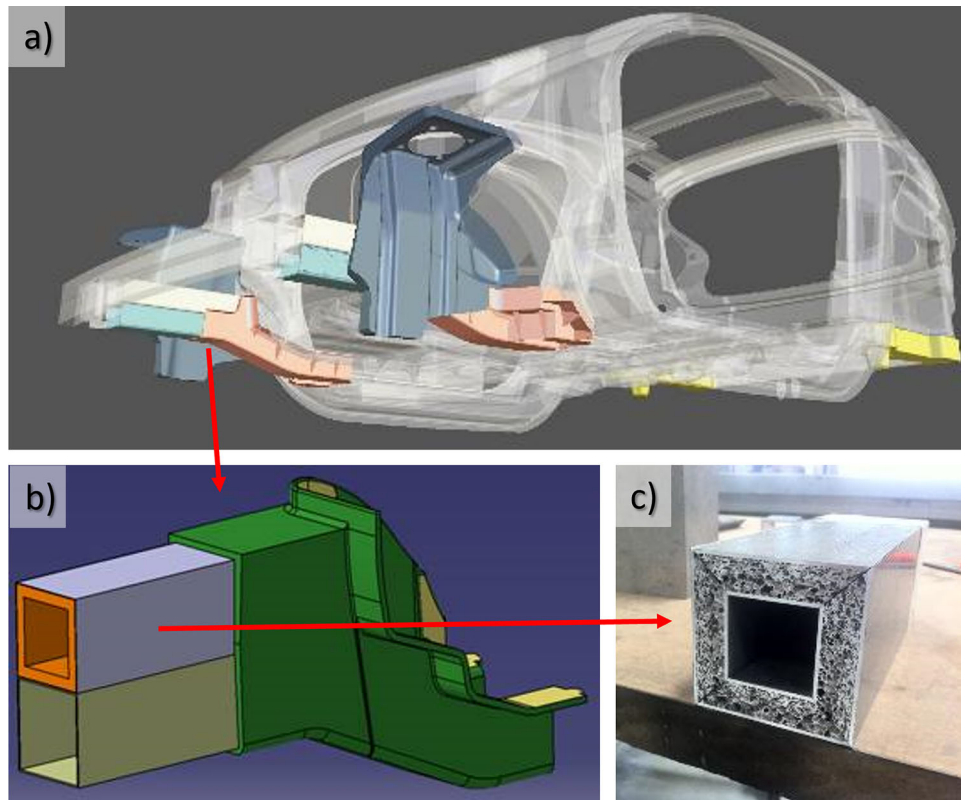


Fig. 8. (a) BIW of the Pininfarina Nido EV showing (b) the position of the bumper support and crash absorber profiles, which were proposed in the frame of the European project “Evolution”⁴⁷ to be substituted by (c) four welded AFS parts (AFS 20/1.5 mm, profile dimensions 80 mm × 80 mm × 250 mm) of less weight and better performance. Reproduced under the terms of the CC-BY license.⁸ Copyright 2016, MDPI.

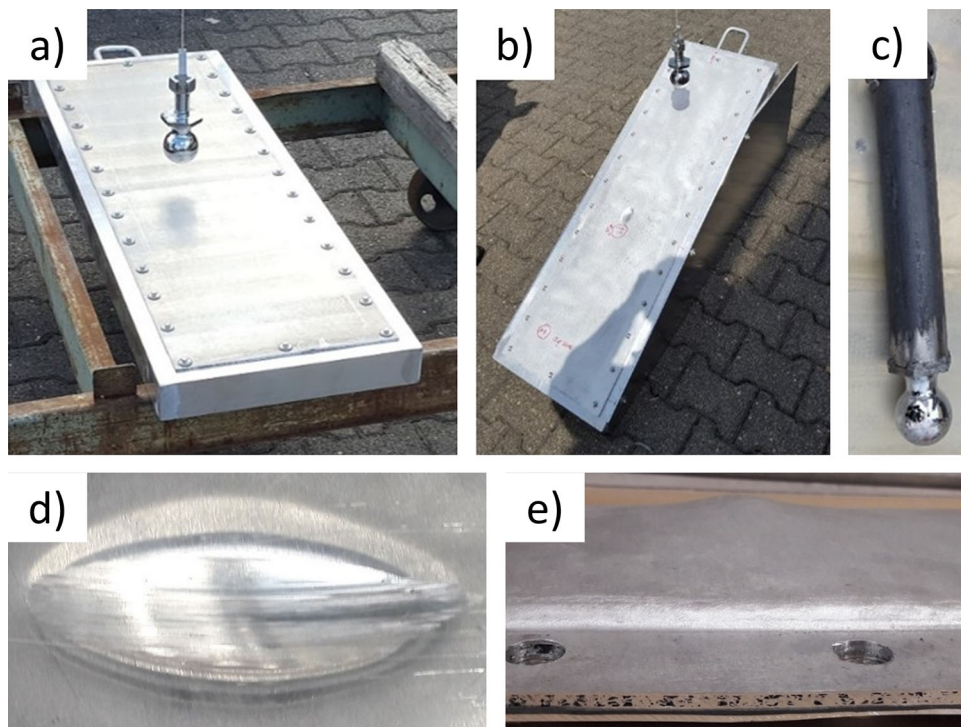


Fig. 9. Impact test configuration: (a) AFS fixed on a frame (analogue to a vehicle) perpendicular to the impact direction and (b) under an angle of incidence of 64°. (c) A modified hitch ball with 5 times more weight was used to simulate impact energies of 112 km/h. Impact results at 112 km/h of two AFS plates with reinforced faces: (d) angle of incidence 26° with an Al face sheet of 1 mm thickness on the impact side, and (e) angle of incidence 64° with an Al plate of 2 mm on the impact side.

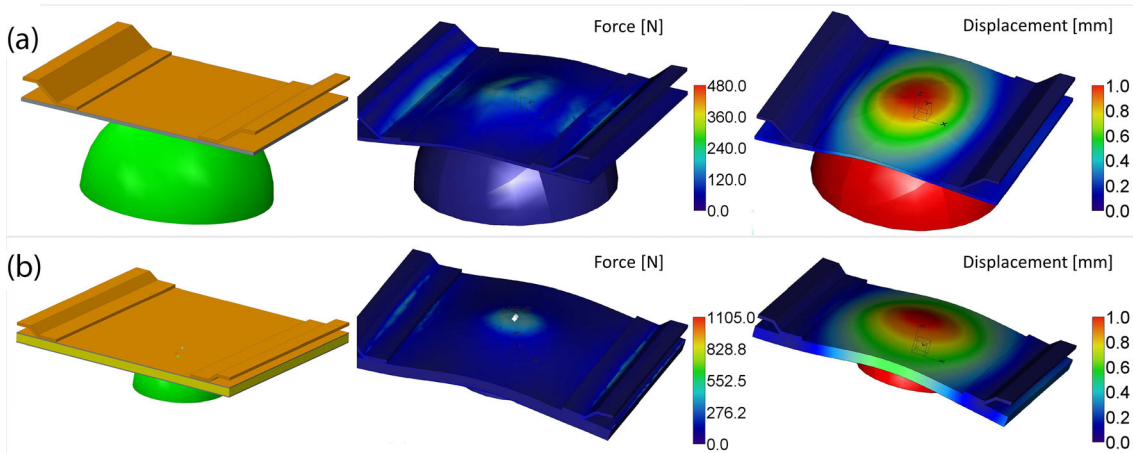


Fig. 10. CAE simulation of a quasi-static impact (green bollard) on a structural system (equal in weight and installation space/height): (a) all Al alloy solution of 3.5-mm-thick plates and profiles; (b) AFS plate (8 mm foam core and 1 mm face sheets thickness) and 3.5-mm-thick profiles. 2.4 kN and 9.8 kN were required to deform the Al alloy solution and the AFS-Al alloy solution to the same extent, respectively. Note that the different sizes of the spheres is due to a visualization problem (Color figure online).

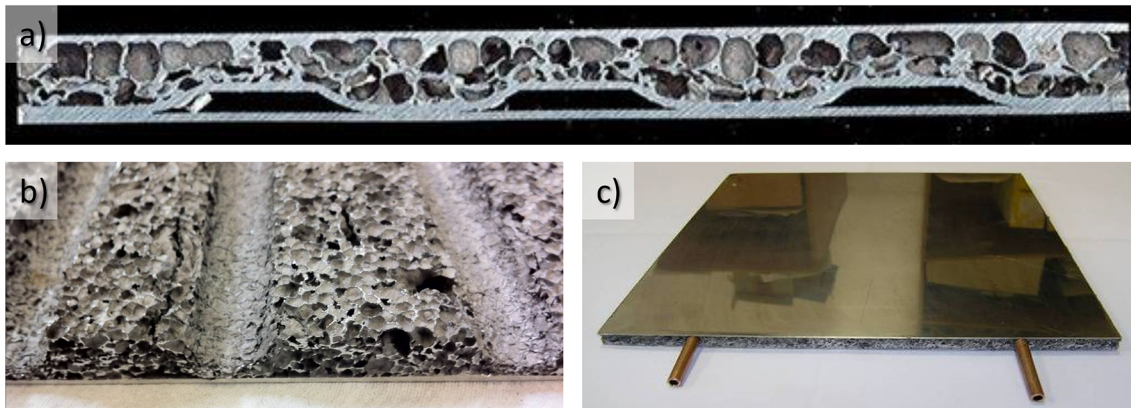


Fig. 11. Cooling concept prototype of AFS with partially densified cooling/heating channels: (a) closed by a brazed Al-alloy-plate, (b) only densified channels on an opened AFS, and (c) with copper tubing inside the AFS.

(9.8 kN) is around 4 times as high as the one for the Al alloy solution (2.4 kN).

These results show impressively that either maximum loads in the case of an accident can be increased or the weight and/or installation space can be reduced. Especially, the decrease in weight and installation space might be the favorable approach for most industrial applications to improve their current standards.

System Cooling

Foams in general are usually linked to heat insulation material, which is certainly the case for ceramic or polymeric ones.⁴⁸ In case of Al foams, although the thermal connectivity of the foam is low, 10–15 W/mK in contrast to 75–235 W/mK of solid Al alloys, we cannot consider it as an insulation material. However, heat dissipates over a larger area of the foam via struts and cell walls, whereby a more homogenous temperature distribution is achieved over a larger surface compared to its

solid pendant.²⁷ This property is useful, e.g., for the temperature control of battery systems in the compartment floor of electric cars. How such channels for thermal regulation might look like in cross-section is seen in a prototype in Fig. 11. Several cooling/heating channels can be implemented by partially local densification, using a closing plate attached to the AFS by a brazing process, as shown in Fig. 11a and b. Another option is to embed steel or copper tubes inside the AFS plate or the metal foam, as shown in Fig. 11c.⁴⁹ A liquid flow can then regulate the heat by air exchange at the frame or vertical struts of the battery box, and provide the system with an elegant functionality.

CONCLUSION

- The electrification of modern vehicles and redesign of BIWs identifies a high potential for lightweight AFS.

- By using AFS in comparison to solid aluminum, the same bending stiffness can be reached with 65% and more than 80% less weight in comparison to steel.
- AFS has the same weight-saving potential for plane parts as CFRP, but is considerably less expensive (investment = 1 €/kg for AFS vs. 3 €/kg for CFRP).
- Simple handling, manufacturing techniques, as well as standard post-production and connection techniques, are applicable.
- AFS presents a combination of lightweight structural material with multi-functional properties, e.g., improved fire resistance and vibration absorption. Furthermore, AFS battery cases with unique crash/impact protection, as well as cooling solutions, are of particular interest for electric vehicles.
- After decades of research, a reliable industrial production process of AFS is now available and ready for mass production.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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