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Investigation of the Use of Aluminum Foam Sandwich in Battery Housings for Electric Vehicles

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Abstract: Aluminum foam sandwich (AFS) offers distinct mechanical properties including good fire protection and the capability to absorb energy in the event of a collision. This makes AFS a promising candidate for battery housings in electric vehicles (EV). It eliminates the decisive disadvantage of short EV range by keeping the weight low while improving safety. By comparing material requirements with the properties of AFS, this paper assesses the potential and the advantages of AFS utilization for battery housing. To prove practical ability a battery housing was constructed.

Keywords: Aluminum Foam Sandwich, Electromobility, Lightweight Design, New Product Development, Design for X (DfX)

1 Introduction

Innovative materials are needed for economical production in the face of scarce resources. With the focus on electromobility, these can help to exploit the full potential. In this context sandwich elements as lightweight materials are one of the barely explored concepts (Kampker et al., 2018; Hantelmann et al., 2015) and particular attention must be paid to aluminum foam sandwich (AFS) as an innovative sandwich material. The material differs from conventional lightweight materials in terms of its mechanical properties.

This is due to the sandwich structure of the two aluminum face sheets and an intermediate foamed aluminum core. Its increased bending stiffness and ability to absorb energy with simultaneous weight savings should be noted (Hantelmann et al., 2015).The structure of AFS is shown in Figure 1.

Figure 1. Structure of AFS in different variations of wall thickness

As a result of European legislation to combat climate change, electric vehicles (EVs) will play a major role in daily mobility in the future (Schwedes et al., 2021; Kampker et al., 2018). It is advantageous to increase the acceptance of EVs among the population by eliminating the decisive disadvantage of their low range (Haustein and Jensen, 2018). A cost-effective and fast way to achieve this is to reduce the vehicle weight with lightweight materials like AFS gaining in importance as part of this approach (VDI, 2014). Because of its major influence on the overall weight of the vehicle, the battery housing represents a promising starting point for increasing range through weight reduction. Positive side effects of the weight reduction of the overall vehicle are less severe damage and impact due to lower crash energy, shorter braking distance, and lower tire wear (Justen and Schöneburg, 2011; VDI, 2014; Sutschet et al., 2023).

2 Problem statement, goal and structure of this paper

The focus on weight reduction has caused safety-related issues such as fire protection and crash behavior to be overlooked. However, these require closer assessment for EVs due to the changed structure and the positioning of the battery on the underbody (Schmerler, 2018). While current approaches to increasing safety lead to an overall weight gain for EVs (VDI, 2014), the use of AFS as a lightweight material is capable of improving safety while maintaining or reducing weight due to its excellent mechanical properties. Crafting the battery housing specifically for AFS while meeting all requirements can unlock the potential of lightweight design and improve market standards in terms of safety. The objective of this paper is to investigate the potential of AFS in the battery housing of EVs and the emerging challenges with the scientific methods of literature work, an evaluating method, design and experiments. The research question is therefore as follows:

What are the potential benefits and resulting challenges that arise from using AFS in battery housings for EVs?

The approach to solving the problem is reflected in the structure of the paper. In the following, Section 3 outlines the state of the art with respect to the fundamentals of AFS and battery housings in EVs. Section 4 first identifies the requirements for a battery housing, then compares these requirements directly with the properties of AFS and uses an evaluation method to assess the extent to which these are fulfilled. This section also provides more detail on the advantageous properties of the housing made of AFS compared to the reference materials. The feasibility and benefits of AFS in battery housings are demonstrated through a reference design in Section 5. The article concludes with a summary and an outlook on the future (Section 6).

3 State of the art on materials and automotive component

The following subsections describe the state of the art regarding the properties and application areas of AFS, the structure, the lightweight materials used, and the current challenges relating to battery housings of EVs.

3.1 Properties and application areas of AFS

The dominant manufacturing process for AFS is the powder metallurgy process in which the face sheets and the core are metallurgically bonded together (Hipke et al., 2007; Hohlfeld et al., 2018; Sviridov, 2011). Manufacturing takes place in plate form with dimensions of up to 2,800×1,400 mm using conventional forming processes with cost-intensive three-dimensional shaping possible (Sviridov, 2011). The thickness of the face and core layers and the density of the core layer can be adjusted for the entire sandwich. A minimum sandwich height of 6-9 mm must be maintained in order to exploit the positive properties of the sandwich. The density depends on the alloys used: For the AFS considered in this work, the density is 2.7 g/cm³ for the face sheet and 0.6 g/cm³ for the core (Batz und Burgel, 2019; Havel metal foam GmbH, 2023b). Only closed-cell aluminum foam is considered in this work because of its suitable mechanical properties for market launch (Banhart, 2005). Guidelines regarding design with AFS and reference applications are limited (Hommel et al., 2021a; Hommel et al., 2021b). The joining technique is adapted to the sandwich structure and the pore structure of the core layer using inserts, which are auxiliaries that are inserted into the sandwich (Hipke et al., 2007). Despite the high potential of AFS in the field of EVs, the number of industrial applications is low (Hommel et al., 2021b) and there is little knowledge relating to series applications. However, a prototype truck battery housing made of AFS does exist (Leichtbauwelt, 2020). It can be assumed that the focus of the development was not primarily on the design, but on the feasibility of integrating the thermal management system in the underbody panel. The prototype can be seen in Figure 2.

Figure 2. Prototype of a battery housing made of AFS with foamed-in tubes according to Fraunhofer IWU (2020)

The positive properties of AFS produced using powder metallurgy have been identified via literature research and are summarized in Table 1. These represent design parameters that are responsible for the selection of the material in the product development process (Hipke, 2001).

Table 1. Overview of the positive properties of AFS

Physical properties	Low density (Sviridov, 2011)
	High mechanical energy absorption capacity (Sviridov, 2011)
	High bending and torsional stiffness (Hipke et al., 2007)
	High thermal insulation (Sviridov, 2011)
	Good sound and vibration damping (Sviridov, 2011)
	High temperature resistance (Hommel et al., 2023)
	Good electromagnetic compatibility (Feldmann et al., 2007)

Chemical properties	High fire protection (Hipke et al., 2007)
	Good corrosion resistance (GdA, 2007)
Ecological properties	High recyclability (GdA, 2007)

From the current, still very limited set of applications that are available in published form, it appears that AFS is specifically of interest for applications that require

- lightweight construction (Banhart, 2005)
- silencers or acoustic absorbers (Patrone et al., 2022)
- blast and projectile protection (Banhart et al., 2019)
- vibration dampers (Harish et al., 2021)
- crash absorber and energy absorber (Banhart et al., 2019)
- or body stiffener (Neugebauer, 2017).

The limited set of applications are attributable to general disadvantages of the material and current challenges, which will decrease with frequent use. The latter was investigated in Hommel et al. (2020) and shows the need of a design support as the main obstacles have been identified as the lack of design knowledge and reference applications as well as which application is suitable for the material. Also mentioned were the high costs. General disadvantages of the material are the insufficiently known material properties and the high scattering of these due to the inhomogeneity in the foam. (Hommel et al., 2020)

Conventional calculation methods necessitate adjustment to accommodate the specific structural composition and characteristic properties of AFS (Hantelmann et al., 2015). Critical to this calculation process is the classification of AFS as a sandwich material. Strength analysis is conducted according to failure criteria specific to sandwich structures, with the particular types of failure being contingent upon the occurrence of certain loads (Torsakul, 2007).

3.2 Battery housing

The battery can be divided into the main components of the battery cell, battery management, and housing (Kleine-Möllhoff et al., 2012). Multiple battery cells form a module, which in turn is assembled in multiple versions in a housing and combines with the battery management system to constitute a vehicle battery (Karle, 2022; Wienands, 2020). By positioning the rectangular battery housing in the underbody between the front and rear wheels, the stiffness of the battery is used to increase vehicle stability, safety, and handling (Schmolke et al., 2021). The battery housing therefore has a significant influence on the safety of the battery technology and on the vehicle occupants in the event of a crash. Conventional battery housings for EVs are made of aluminum or steel (Schludi and Joos, 2019), although numerous studies exist on the use of fiber-reinforced plastics (Schwarzl et al., 2022). Current issues and challenges in battery housings include weight reduction, negative correlation between crashworthiness and lightweight materials (Schmolke et al., 2021), structural redundancies (Schmolke et al., 2021), and sustainability (Windisch-Kern et al., 2022).

The main component of the housing is a one-piece tray with a housing cover, which is supplemented by a battery frame acting as a crash frame and by a lower protection cover with a separate cooling system. The modules are positioned according to the crash structure, which also provides the load line paths. (Schmolke et al., 2021) An example structure of an aluminum battery housing can be seen in Figure 3.

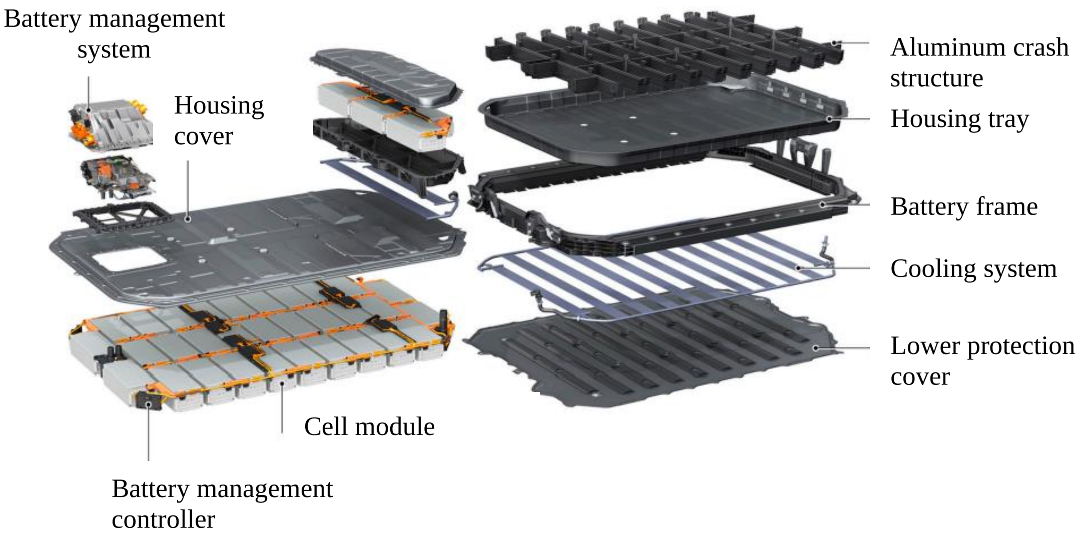


Figure 3. Example structure of a battery housing according to Audi Media Center (2022)

4 Investigating the potential of AFS for battery housings in electric vehicles

In preparation for the analysis of the theoretical potential of AFS, it is necessary to identify the general requirements for battery housing material.

4.1 Identification of the basic requirements for the material

The basic requirements for the material of the battery housing are identified by means of a search based on the example structure in Figure 3 or derived from regulations. The requirements consist of regulatory, functional, and general criteria. The latter are largely based on customer requirements and are therefore implicitly stated (Zimmermann and de Weck, 2020).

The regulatory requirements are derived from standardized tests, although no globally unified standard exists with regard to the testing and approval of lithium-ion batteries and their housings for EVs. Requirements are therefore derived from European standards: ECE-R100 (UNECE 2015) includes tests for approval while UN 38.3 (UN, 2015) defines tests for approval for transport. These are complemented by the tests of the car manufacturers, which are not published and therefore not considered here. The tests defined in the standards correspond to the minimum requirements that must be met. In general, the high safety requirements are due to the great danger posed by the use of high amounts of energy, the chemicals in the battery cells, and the low mechanical load capacity of the battery cells (Kleine-Möllhoff et al., 2012; Schmolke et al., 2021). In the event of a crash, the battery housing protects the battery technology and the vehicle occupants (Schmolke et al., 2021) by ensuring a time window of several minutes for exiting the vehicle in the potential event of a fire (Doppelbauer, 2020). ECE-R100 includes mechanical, thermal, and electrical test types, with the latter not considered in this paper due to their lack of relevance for the battery housing. The UN 38.3 tests largely overlap with ECE-R100, which is why only the height simulation is considered as an additional mechanical test. Since the tests can be performed for both the pack and module level, not all of them are relevant for deriving the requirements for the material of the housing (pack level). The requirements arising from the relevant tests are generalized and identified as vibration, pressure, and shock resistance. The entirety of the thermal tests for the battery housing is used to determine whether the battery housing can withstand a thermal runaway (Pfitzinger, 2021). In the event of a thermal runaway, the battery cell burns or explodes, creating an abrasive gas jet with particles of the battery cell. The battery housing protects the neighboring components and the vehicle occupants from consequential damage (Pfitzinger, 2021). For this purpose, svt Products GmbH has developed a particle impact test that provides an indication of whether the battery housing would withstand a thermal runaway (Pfitzinger, 2021). The test procedure is described in 4.2. Rather than considering all the tests in the standard individually, only the particle impact test needs to be performed to simulate the acting load in terms of temperature, pressure, and particles. The particle impact test, which has been conducted on over 200 materials, is not a one-to-one substitute for the individual tests, but provides a reliable indication of whether the thermal tests are passed.

The functional requirements for the material result from the various functions of the battery housing and are not standardized. Due to the positioning of the battery housing in the floor, the battery housing influences the static and dynamic stiffness of the entire vehicle and thus also the safety in the event of a crash (Schwarzl et al., 2022). High rigidity and strength of the battery housing are required for structural integrity. To protect the vehicle occupants and prevent damage or thermal runaway of the battery, the battery housing should have a high energy absorption capacity. Since the performance is highly temperature-dependent and deviations from the target range lead to a reduction of the battery cell service life, thermal management of heating and cooling processes is essential (Xia et al., 2017). This can be made easier by high thermal insulation or conduction. The service life of the battery housing should at least correspond to the service life of the battery technology, which is ten years (Kleine-Möllhoff et al., 2012). The durability of the material is influenced by corrosion resistance and resistance to chemicals, so the material should also pass these requirements. To protect the electronics from interference, electromagnetic compatibility must be established either by the material or by the design. To protect the battery cells from water, moisture or dust penetration, the material and design must meet the IP67 standard (Schmolke et al., 2021).

General requirements for the material are recyclability to ensure sustainability, low density to achieve the desired weight reduction, and low material and manufacturing costs to increase the acceptance of the battery housing among the population. All of the requirements are summarized in Table 2.

Table 2. Collection of requirements for the material of battery housing of EVs

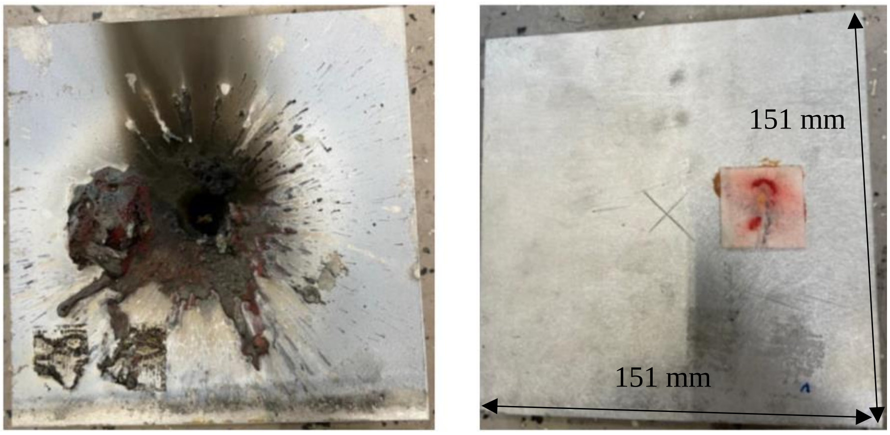
Regulatory requirements	Vibration, pressure and shock resistance (mechanical tests)
	Passing the particle impact test (thermal tests)

Functional requirements	High rigidity and strength, high energy absorption capacity, high durability, high thermal insulation or conduction, corrosion resistance, resistance to chemicals, electromagnetic capability
General requirements	Recyclability, low density, low material and manufacturing costs

4.2 Comparative analysis of the requirements and properties of AFS

In the following, it is necessary to assess the fulfillment of the requirements for the material of battery casings listed in Table 2 via a comparison with the properties of AFS. If all requirements are met by AFS, then it is possible to use AFS in a battery housing.

It is not possible to make a reliable statement about the passing of the regulatory mechanical tests, as this can only be verified on the basis of crash tests (Schmolke et al., 2021). But since AFS exhibits fundamentally good mechanical properties comparable to state-of-the-art materials, which have passed the admission, it is therefore assumed that the mechanical tests will be passed. As mentioned in Section 4.1 the assessment of compliance with the thermal requirements is based on the performance of the particle impact test. This involves bombarding an AFS plate featuring a wall thickness of 15 mm with particles at a temperature of up to 1,400°C while the temperature curve is measured. This simulates the conditions during a thermal runaway, encompassing the abrasive particles and the rupture of the outer shell (Pfitzinger, 2021). The wall thickness corresponds to that of the reference design presented later on. The results of the particle impact test conducted with AFS can be seen in Figure 4.



$$\rho_{\mathrm{core}} = 0.84\,\frac{\mathrm{g}}{\mathrm{cm}^3}$$

$$\rho_{\mathrm{face\ sheet}} = 2.7\,\frac{\mathrm{g}}{\mathrm{cm}^3}$$

$$t_{\mathrm{face\ sheet}} = 1.5\ \mathrm{mm}$$

$$t_{\mathrm{core}} = 12\ \mathrm{mm}$$

$$t_{\mathrm{overall}} = 15\ \mathrm{mm}$$

Figure 4. AFS test specimen after particle impact on the exposed surface (left) and the unexposed surface (right)

The unexposed surface of the AFS plate is undamaged, supporting the conclusion that AFS in the present wall thickness of 15 mm can withstand a thermal runaway. It is assumed that the abrasive particles are scattered by the pore structure and thus lose their intensity. In terms of the test result, this provides maximum protection for the environment. The temperature on the back, which corresponds to the inside of the battery housing, is also comparatively low at 160°C with AFS. The functional and general requirements are met, as can be concluded from the description of the properties of AFS in the previous section.

4.3 Identifying the advantages of AFS over conventional lightweight materials

The advantages are identified by taking the structure of the battery housing and the improved properties, then comparing these with the reference materials currently on the market (steel, aluminum). An evaluation method is then introduced to show which material best fulfills the property profile identified in Section 4.2.

When AFS is used as the material for the battery housing, there is increased functional integration. This is associated with the elimination of components, which simplifies the design of the housing and taps into the potential of lightweight design. There is also the possibility of integrating pipes for liquid cooling in the underbody, making the cold plate redundant (Havel metal foam GmbH, 2023a). The ability to absorb crash energy at the sidewalls and the floor can lead to the elimination of the lateral crash structure and lower protection cover.

Numerous advantageous properties can be accessed by changing from conventional lightweight materials listed in the state of the art to AFS. The material change has a positive effect on thermal management. As a result of the heat-insulating properties of AFS, less energy is required for thermal management by the traction battery, thus increasing the range. Passive safety is also increased by the ability to absorb energy, which results in greater protection for vehicle occupants and battery technology in the event of a crash. The high torsional and bending stiffness improves the stability and crash behavior of the entire vehicle (Schwarzl et al., 2022). The increased surface moment of inertia due to the sandwich structure ensures low deflection and thus low damage to the battery housing in the event of a crash. In combination with the controlled thermal management, the probability of occurrence and the consequences for the environment in the event of a thermal runaway are reduced. The latter has been demonstrated for AFS via the particle impact test in Figure 4. The result of the particle impact test for an aluminum plate with a wall thickness of two millimeters is shown in Figure 5. The aluminum plate burns out after five seconds. Contrary to AFS, it cannot withstand a thermal runaway that can cause a fire or explosion (Wang et al., 2012). Vehicle occupants in a car with an aluminum battery housing featuring this wall thickness are at great risk from the consequences that occur during a thermal runaway. Vibration damping increases comfort and reduces costs by extending maintenance intervals and increasing service life. Sound damping also influences comfort. Both points lead to better driving behavior, which has an influence on the customer's willingness to buy. The manufacturing costs are low because the housing is made of flat plates, eliminating the need for tooling. The use of AFS makes it possible to tap into the potential of lightweight design. A direct comparison of weight can only be performed using a calculated wall thickness from Banhart et al. (2019) with identical material strength for each material. Despite the higher wall thickness, AFS weighs less than aluminum and steel. Sustainability is ensured by the fact that AFS can be reintegrated into existing material cycles by melting it down (GdA, 2017). AFS exhibits good electromagnetic compatibility, which is a result of the sandwich structure and the porous core layer (Feldmann et al., 2007). Given the lack of previous studies involving AFS, detailed examination is necessary to determine the impact of the improvement. In summary, all challenges and problems described in the state of the art can be optimized or solved by AFS and additional advantages result.


$t_{\mathrm{aluminum}} = 2\ \mathrm{mm}$

Figure 5. Particle impact test on an aluminum plate

In order to be able to systematically evaluate the fulfillment of all requirements for the materials, an evaluation method has been developed. Functional and general conditions from Table 2 are the requirements to be assessed. The regulatory requirements are not considered, as no ranking can be derived (results are only pass or fail). In addition, it can be inferred from the market approval of battery housings made of aluminum and steel that they meet the regulatory requirements. For AFS the justification is given in Section 4.2. Specific evaluation criteria have been defined for each requirement, all of which ensure that the materials can be compared as uniformly as possible. The aim is to find the most suitable battery housing material by evaluating the fulfillment of all requirements for every material with a score from zero to four. AFS and the competing materials (aluminum and steel) are assessed. The four-point Likert scale is introduced to enable precise differentiation between the materials in terms of fulfillment of properties. Points are preferably allocated based on established material properties that align with the specified requirements. If no material property data are available, criteria are formulated for the pertinent requirements. Theoretical deliberations are then conducted to facilitate a comprehensive assessment, achieved through the analysis of material behavior encompassing aspects such as chemical, physical, mechanical, and other pertinent factors. An overall ranking can be derived from the average score and the individual requirements are not weighted. The outcome of the evaluation method is presented in Table 3. As can be seen from Table 3, AFS does not only fulfill the properties mentioned above but also surpasses both aluminum and steel in meeting functional and general requirements.

Table 3. Result of the evaluation method

	0 = not fulfilled 1 = partial fulfilled 2 = adequately fulfilled 3 = substantialy fulfilled 4 = fully fulfilled	Materials		
	Requirements	AFS	Aluminum	Steel
Functional	High rigidity and strength	2	3	4
	High energy absorption capacity	4	2	1
	High durability	4	4	4
	High thermal insulation or conduction	4	3	1
	High corrosion resistance	3	3	1
	High resistance to chemicals	3	3	1
	High electromagnetic capability	4	3	2
General	High recyclability	3	3	4
	Low density	4	3	1
	Low material and manufacturing costs	2	3	4
Overall score (ranking)		**3,3 (1)**	**3,0 (2)**	**2,3 (3)**

5 Design of a battery housing

The basic theoretical suitability and advantages of AFS as a material for the battery housing of an EV have been demonstrated in the previous section. The practical implementation and feasibility must be demonstrated by means of a reference design.

The application in question is the battery housing of an electric racing car. This housing has been developed especially for participation in Formula Student and is currently made of aramid. The design is realized in accordance with AFS so as to profit from the advantages of this material listed above. The basic requirements and functions from the previous section are transferred to a list of requirements, then supplemented by specific requirements on the part of the development team and Formula Student regulations. Given that the components of the battery housing are largely uniform and that the design is founded upon the requirements outlined in Section 4.1, it can readily be adapted for use in EVs. Nevertheless, some requirements are not imposed within the framework of the Formula Student regulations: One is the tightness at the interface between the cover and the housing, while another is the thermal management implemented with an air-cooling system that is insufficient for an EV. The tightness can be solved by design and relevant literature e.g. (Schmerler, 2018; Havel metal foam GmbH, 2023b) is available for the integration of thermal management in AFS. The composition of the battery housing from flat plates means that the manufacturing costs are comparatively low because no tooling is required.

The basis for the design is the CAD model of the current battery housing used by a university team. The process of reverse engineering identifies locations on the battery case that are feasible for the application of AFS only with modification of the current concept or whose potential could be increased by targeted modifications in combination with the use of AFS. The focus is on manufacturing technology, lightweight potential, economy, and strength. Solution variants for all positions are generalized in an order scheme that can be applied to battery housings in EVs. The calculation of the wall thickness is based on the approach of having the same strength as the current housing made of aramid. For this purpose, the forces acting on the housing and the highest load point are defined via a strength calculation and the wall thickness of the housing is calculated according to sandwich theory (15 mm in this case). The wall thickness of the EV is estimated at 20 mm because of the higher overall vehicle weight and structural integrity. As a result of the increased wall thickness, increased weight, and limited available installation space, AFS is only used on those sides of the battery housing where there is crash potential and where AFS can therefore be used profitably. According to Justen and Schöneburg (2011), this is true of the side walls, partition walls, and floor panel of EVs. In this application, the floor, side walls, and rear walls are made of AFS. The material for the remaining components can be selected from lightweight materials, considering the compatibility of joining methods, tightness at interfaces and prevention of contact corrosion. With main dimensions of 655×304×178 mm, the weight of the unfilled battery housing with the other components made of aluminum is 10.19 kg. For the EV application, it is difficult to classify the weight due to the different safety levels of the housings and the functional integration of the AFS housing, which makes some components redundant. Based on the comparison with data sheets of competitor products on the market, it can be said with certainty that the AFS housing will be at least between aluminum and steel in terms of weight keeping in mind that the AFS housing offers a much higher level of safety compared to the other twos. The outer surface layer is closed by welding seams or the use of the routing and folding method according to Binz et al. (2018) in order to meet the requirement for tightness and to prevent corrosion. The application of a seal is only possible on the face sheet because of the required service life. Contrary to battery housing made from conventional lightweight material, the design provides for a glue-free housing, so there are none of the restrictions on recycling, service life, temperature resistance, and fire protection that would result from chemical stocks in the adhesive. The joining technology requires new thinking due to the use of inserts and the need to include a face sheet to maintain sufficient pull-out force. This opens up new possibilities, such as bolting the battery modules into the side panels. The individual parts of the constructed housing without the bolting can be seen on the left and the entire assembled housing can be seen on the right in Figure 6.

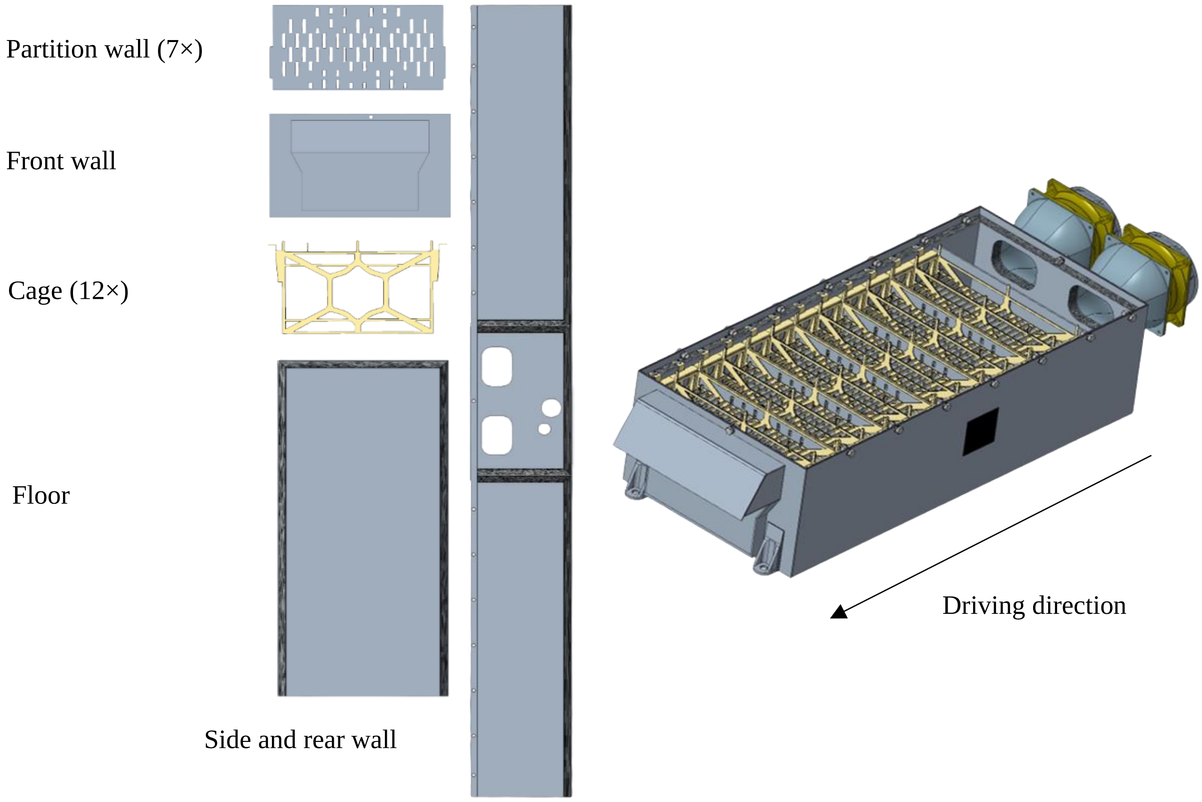


Figure 6. Battery housing made of AFS with individual components (left) and assembled product (right)

The design shows the feasibility of the battery housing made of AFS. In addition to utilizing the positive properties of AFS, this application is also suitable because only flat panels are required. The new design, which has to be adapted for use in EVs in terms of dimensions, seals and thermal management, opens up new design possibilities. For example, in thermal management, where cooling with ambient air is not sufficient, pipes or inlets and outlets for the refrigerant of the base and side walls can be foamed in (Havel metal foam GmbH, 2023a). This utilizes the wall thickness of the material and no new components or additional space is required.

The increase in wall thickness and the associated weight gain compared to the aramid housing can be compensated for by the functional integration and profitable properties of AFS. These include improved safety for battery technology and vehicle occupants in the event of a crash by means of energy absorption and by reducing both the probability of occurrence and the consequences of a thermal runaway.

6 Conclusion and outlook

Lightweight materials such as AFS are relevant for weight savings and the associated increase in range for EVs. AFS also has the potential to increase safety, which is normally negatively correlated with conventional lightweight materials. The battery housing of an EV represents a promising example application of AFS.

In order to analyze the potential of AFS for this application, the regulatory, functional, and general requirements for the battery housing material have been elaborated by research or were derived from regulations. By comparing these with the properties of AFS, it has been shown that AFS meets all the requirements for the application and also offers many advantages over conventional battery housings made of aluminum or steel. The fact that AFS passes the thermal test from the regulations is demonstrated by its ability to withstand the particle impact test, which simulates the conditions of a thermal runaway. The potential for lightweight design is ensured by the omission of the crash frame and the cooling plate, for example while the safety of the battery housing is increased by the energy absorption capacity (passive safety) and the ability to withstand thermal runaway (fire protection). Other positively influenced properties are the extended durability and the improved comfort, provided by the vibration damping in which AFS differs from conventional materials for battery housings. The evaluation method indicates that AFS fulfills the requirements for the material of a battery housing better than the competitor materials. The basic potential of AFS as a battery housing in this application has therefore been demonstrated. With the battery housing made of AFS, an application has been found that combines all previously identified areas of application in a single application, so that all the advantageous properties are utilized in this application. The implementation of an example design, which was realized for the application of an electric racing car and is transferable with a few adaptions to EVs, shows that AFS is feasible and that all previously identified advantages of AFS can be put into practice. The design was adapted to the conditions of the material, which benefited from the fact that the structure consists of flat panels, thus eliminating the need for cost-intensive production. The result is a battery housing which, while weighing approximately the same as the current competitor materials on the market, clearly stands out from the state of the art with its improved properties due to its increased safety in the event of a crash (absorption of crash energy and reduced deflection) and, above all, its ability to withstand a thermal runaway, simulated by the particle impact test. The increase in wall thickness that occurs can be compensated for by functional integration and the advantageous properties described. It is only possible to make an exact statement on weight reduction once the wall thickness and the material selection for the structure have been determined.

It is also necessary to undertake further investigations into the reduction of the wall thickness with consequential effects on the weight. Simulations with the aim of determining a reasonable minimum wall thickness for AFS are recommended. The result can be tested in cooperation with svt Products GmbH to determine whether it passes the required particle impact test.

At the outset, the approach outlined in this paper streamlines the complex and resource-intensive testing procedures stipulated by several standards. However, it is imperative to validate the transferability of the results before extrapolation, given the simplified nature of the tests. Due to the significant influence of the core layer on the outcome, the results are confined to the manufacturing process and the wall thickness distribution of the AFS utilized. Furthermore, the results cannot be extrapolated to extreme testing conditions such as heat or cold. The high potential of AFS in battery housing application was demonstrated, a definitive assessment of whether AFS complies with the prescribed testing standards can only be attained by conducting the standardized tests on a housing that closely replicates real-world conditions.

References

Audi Media Center, 2022. Der neue Audi Q8 e-tron: Mehr Kapazität und höhere Ladeleistung: die Batterie. [online] Audi Media Center. Available at https://www.audi-mediacenter.com/de/der-neue-audi-q8-e-tron-15069/mehr-kapazitaet-und-hoehere-ladeleistung-die-batterie-15072 (accessed 12.04.2024)

Banhart, J., 2005. Metal foams-from fundamental research to applications, Frontiers in the Design of Materials, 279-289.

Batz und Burgel, 2019. Aluminium-Halbzeug EN AW 6082. [online] Batz und Burgel GmbH. Available at https://batz-burgel.com/metallhandel/lieferant-aluminium/en-aw-6082/ (accessed 07.05.2023).

Binz, H., Honold, C., Laufer, F, Hommel, P., 2018. Konstruktion und Herstellung eines Auslegers aus Aluminiumschaum-Sandwich unter Anwendung der Fräskanttechnik, Konstruktion, 78-82.

Doppelbauer, M., 2020. Grundlagen der Elektromobilität. Technik, Praxis, Energie und Umwelt, Springer, Wiesbaden/Heidelberg.

Feldmann, K., Geiger, M., Kreis, O., Schüßler, F., 2007. Fertigungstechnik in Erlangen, Zeitschrift für wirtschaftlichen Fabrikbetrieb 102, 98–99.

Fraunhofer IWU, 2020. Metallschaum macht Elektro-Lastkraftwagen sicherer und umweltverträglicher. [online] Fraunhofer IWU. Available at https://www.iwu.fraunhofer.de/de/presse-und-medien/presseinformationen (accessed 19.04.2024)

Gesamtverband der Aluminiumindustrie e.V. (GdA), 2007. Aluminiumschäume. Herstellung, Anwendung, Recycling, Gesamtverband der Aluminiumindustrie GDA, Düsseldorf.

Banhart, J., Garcia-Moreno, F., Heim, K., Seeliger, H.-W., 2019. Light-Weighting in Transportation and Defence Using Aluminium Foam Sandwich Structures, in: Gokhale, A., Prasad, N., Biswajit, B. (Eds.), Light Weighting for Defense, Aerospace, and Transportation, Springer, Singapore, pp. 61-72.

Hantelmann, C., Fritzsche, S., Michailov, V., Risse, S., Boxwitt, R., et al., 2015. Gestaltungshinweise für geschweißte Konstruktionen aus Aluminiumschäumen, AiF Forschungsvorhaben, Cottbus.

Harish, S., Jeyanthi, S., Abinash, M., Suresh Kumar, R., Agarwal, S., Venkatachalam, G., 2021. Study of thermal behavior of Aluminium foams in batteries of electric vehicles, International Conference on Applications in Computational Engineering and Sciences, Chennai, India, October 30-31, IOP Conference Series: Materials Science and Engineering, pp. 1-8.

Haustein, S., Jensen, A., 2018. "Factors of electric vehicle adaption: A comparison of conventional and electric car users based on an extended theory of planned behavior", International Journal of Sustainable Transportation 12, 484-496.

Havel metal foam GmbH, 2023a. 3D-Sandwiches aus Metallschaum. [online] Havel metal foam GmbH. Available at https://www.havel-mf.com/produkte/id-3d-sandwiches (accessed 03.10.2023).

Havel metal foam GmbH, 2023b. Product Data Sheet. Aluminium-Aluminium foam-Sandwich (AAS). [online] Havel metal foam GmbH. (accessed 08.07.2023).

Hipke, T., 2001. Analyse, Bewertung und Eignung von Aluminiumschäumen für die Werkzeugmaschinenkonstruktion, [PhD thesis], University of Technology Chemnitz.

Hipke, T., Lange, G., Poss, R., 2007. Taschenbuch für Aluminiumschäume, Aluminium-Verlag, Düsseldorf.

Hohlfeld, J.; Hipke, T.; Schuller, F., 2018. Sandwich manufacturing with foam core and aluminum face sheets-A new process without rolling, Materials Science Forum 944, 3-10.

Hommel, P., Roth, D., Binz, H., 2020. Deficits in the application of aluminum foam sandwich: An industrial perspective, 16th International Design Conference, October 26-29, 2020, Cambridge University Press, pp. 927–936.

Hommel, P., Roth, D., Binz, H., 2021. Derivation of motivators for the use of aluminum foam Sandwich and advantageous applications, International Conference on Engineering Design (ICED 2021), Gothenburg, Sweden, August 16-20, pp. 933–942.

Hommel, P., Roth, D., Binz, H., 2021. Überwindung der Herausforderungen beim Konstruieren mit Aluminiumschaum-Sandwich, Stuttgarter Symposium für Produktentwicklung SSP, Stuttgart, Germany, May 20, pp. 305-316.

Hommel, P., Roth, D., Binz, H., Kreimeyer, M., 2023. Methode zur Bewertung des Einsatzpotenzials von Aluminiumschaum-Sandwich, Stuttgarter Symposium für Produktentwicklung SSP, Stuttgart, Germany, May 25, pp. 199-210.

Justen, R., Schöneburg, R., 2011. Crash Safety of Hybrid- and Battery Electric Vehicles, International Technical Conference on the Enhanced Safety of Vehicles, Washington D.C., June 13-16, pp. 1-9.

Kampker, A., Vallée, D.; Schnettler, A., 2018. Elektromobilität, Springer Vieweg, Berlin.

Karle, A., 2022. Elektromobilität. Grundlagen und Praxis, Carl Hanser Verlag, Munich.

Kleine-Möllhoff, P., Benad, H., Beilard, F., Esmail, M., Knöll, M., 2012. Die Batterie als Schlüsseltechnologie für die Elektromobilität der Zukunft: Herausforderungen-Potenziale-Ausblick. Diskussionsbeitrag. Reutlingen, Reutlingen University.

Neugebauer, R., 2017. Entwicklung geeigneter Verbindungselemente zum Fügen von Metallschaum und dessen Halbzeugen.

Patrone, G.L., Paffumi, E., Otura, M., Centurelli, M., Ferrarese, C. et al., 2022, Assessing the Energy Consumption and Driving Range of the QUIET Project Demonstrator Vehicle, Energies 15.

Pfitzinger, A., 2021. Geringes Gewicht bei hoher Sicherheit: Leichtbau inclusive Brandschutz für E-Auto-Batterien, emobility tec, 4, 38-40.

Schludi, C., Joos, J., 2019. Leichte und sichere Batteriegehäuse aus Faserverbundwerkstoff, Lightweight Design 12, 44-47.

Schmerler, R., 2018. Entwicklung von Metallschaumkomponenten für Batteriegehäuseanwendungen und deren Charakterisierung, Fraunhofer-Insitut für Werkzeugmaschinen und Umformtechnik IWU.

Schmolke, T., Krüger, C., Merdivan, D., Spohr, S., 2021. Entwicklung einer gewichtsoptimierten Batteriegehäusestruktur für Volumenfahrzeuge, FAT-Schriftenreihe 352, 1-134.

Schwarzl, W., Hecht, M., Mokina, T., Lienhart, C., 2022. Batteriegehäuse in Stahlbauweise für die Großserie, ATZ - Automobiltechnische Zeitschrift 124, 26-31.

Schwedes, O., Keichel, M., Ahrend, C., Leggewie, C., Ruppert, W. et al., 2021. Das Elektroauto, Springer Vieweg, Wiesbaden/Heidelberg.

Sutschet, A., Bause, K., Bischofberger, A., Ott, S., 2023. Feinstaubemissionen trockenlaufender Friktionssysteme in Fahrzeugen, Forschung im Ingenieurwesen 4, 521-528.

Sviridov, A., 2011. Leichtbau mit Aluminiumschaumsandwich: Prozessketten zur Herstellung von Bauteilen, [PhD thesis], Brandenburg University of Technology Cottbus.

Torsakul, S., 2007. Modellierung und Simulation eines Verbundes von Sandwichplatten zur Entwicklung einer mechanischen Verbindungstechnik. Dissertation, Rheinisch-Westfälische-Technische Hochschule Aachen, Aachen.

United Nations (UN), 2015. Recommendations on the transport of dangerous goods-manual of Tests and Criteria, United Nations, New York and Geneva.

United Nations Economic Commission for Europe (UNECE), 2015. Regulation No 100 of the Economic Commission for Europe of the United Nations (UNECE)-Uniform provisions concerning the approval of vehicles with regard to specific requirements for the electric power train, Official Journal of the European Union.

Verein Deutscher Ingenieure E.V. (VDI), 2014. Studie der Werkstoffinnovationen für nachhaltige Mobilität und Energieversorgung, VDI-Gesellschaft Materials Engineering, Düsseldorf, Germany.

Wang, Q., Ping, P., Zhao, X., Chu, G., Sun, J., Chen, C., 2012. Thermal runaway caused fire and explosion of lithium ion battery, Journal of Power Sources 208, 210–224.

Wienands, S., 2020. Die Lithium-Ionen-Batterie-Grundlagen: Anwendungen und Zukunftsperspektiven, Bern University of Applied Sciences.

Windisch-Kern, S., Gerold, E., Nigl, T., Jandric, A., Altendorfer, M. et al., 2022. Recycling chains for lithium-ion batteries: A critical examination of current challenges, opportunities and process dependencies. Waste management 138, 125–139.

Xia, G., Cao, L., Bi, G., 2017. A review on battery thermal management in electric vehicle application, Journal of Power Sources 367, 90-105.

Zimmermann, M., de Weck, O., 2021. Formulating Engineering System Requirements, In: Maier, A., Oehmen, J., Vermaas, P.E. (Eds.), Handbook of Engineering System Design, Springer, Cham, pp. 1-52.

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