Applications of Aluminium Hybrid Foam Sandwiches in Battery Housings for Electric Vehicles

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Abstract

Light-weight design is of special importance for purely electrical driven vehicles in order to improve driving range and market acceptance. In the project “SmartBatt” – funded by the EC under the 7th Framework Programme – a 20 kWh battery pack was developed which exhibits a 10-15% weight reduction as compared to the State of the Art. Besides an improved integration of the battery pack into the body of white a new sandwich material concept for the battery housing was used to accomplish this. Core of the innovative sandwich technology is to place polymer-coated aluminium foam granules between pre-moulded aluminium face sheets. Dedicated subsequent foaming of the polymer will result in a sandwich structure whose core layer consists of aluminum foam spheres embedded in a matrix of polymer foam. This approach allows excellent process control and the production of components with targeted local sandwich design. The mechanical properties of AlSi10-Epoxy hybrid foams was determined using quasi-static and dynamic compression tests and compared to the behavior of epoxy-mono-foams.

Kurzzusammenfassung

Leichtbau ist für rein elektrisch angetriebene Kfz von besonderer Bedeutung, um die Reichweite zu erhöhen und die Marktakzeptanz zu verbessern. Im Projekt “Smart-Batt” – gefördert im Rahmen des 7. Rahmenprogramms der EU – wurde eine 20 kWh-Batterie-Packung entwickelt, welche 10-15% Gewichtsreduktion gegenüber dem Stand der Technik aufweist. Neben einer verbesserten Integration in die Rohkarosserie wurde ein neues Sandwich-Materialkonzept für das Batteriegehäuse eingesetzt, um dieses Ziel zu erreichen. Kern der neuen Sandwich-Technologie ist, polymerbeschichtetes Aluminiumschaum-Granulat zwischen vorgeformte Aluminium-Decklagen-Bleche zu platzieren. Gezieltes anschließendes Aufschäumen des Polymers führt zur Ausbildung einer Sandwich-Struktur, deren Kernlage aus einer Polymerschaum-Matrix mit integrierten Aluminiumschaum-Kugeln besteht. Der Fertigungsansatz erlaubt eine hervorragende Prozesskontrolle und die Fertigung von Komponenten mit lokaler Sandwich-Auslegung. Die mechanischen Eigenschaften von lSi10-Epoxy-Hybridschaum wurden mittels quasi-statischen und dynamischen Druckversuchen ermittelt und mit dem verhalten von Epoxy-Monoschäumen verglichen.

Keywords: Sandwich, Hybrid foam, Aluminium-polymer composite, Electric mobility, Battery

1 Introduction

The reduction of CO_2-emissions is a sine qua non for the mitigation of the effects of the global climate change. In the field of individual transport systems electric driven vehicles (EV) offer a great potential for CO_2 reductions - especially if combined with renewable energy sources. However, despite the efficient electric drive train modern EV´s suffer from the small amount of energy stored in their batteries. The consequences - constrained driving range, a high volume and a high weight of the battery system - limit the consumer acceptance. In order to overcome these problems the energy density of the battery packs for EV has to be improved significantly. In recent years battery development focused on the chemical approach to enhance the energy density of the used chemistry. A second, additional approach is to maximize the energy density by reducing the weight of the battery pack while the energy content is fixed. This approach was followd in the project "Smart and Safe Integration of Batteries in Electric Vehicles – SmartBatt" (www.smartbatt.eu) with the aim to design and build up a 20 kWh battery pack which is 10-15% lighter than a comparable State of the art solution. In order to reach the overall weight reduction target a significant improvement of the design of the battery housing and its integration into the body-of-white (BIW) had to be reached, see Table 1.

Table 1. Comparison of the state of the art and the SmartBatt-target for the chosen example system, a purely electric car with 20 kWh battery (~200 kg):

Tabelle 1: Vergleich des Stands der Technik und der SmartBatt-Zielkenngrößen für das gewählte Beispielsystem, ein rein elektrisch angetriebenes Kfz mit einer 20kWh Batterie (~200 kg):

	State of the art	Technical target
cells	120-140 kg	unchanged
components	20–30 kg	unchanged
housing	30–60 kg	10-20kg (-66%)
overall battery	**200kg**	**170-180kg (-15%)**

The technological approach was two-fold: a first step was to integrate the battery housing into the body floor structure, i.e. the floor structure is used as top of the battery housing. This means that the battery case is no longer a separate supplement but a fully integrated and basic structural component of the vehicle body; see Fig. 1 and Fig.2. This approach leads to a weight reduction as well as to an enhanced crash safety of the vehicle. The second weight-reducing step was to manufacture the bottom part of the battery housing from aluminium foam sandwich materials. Different sandwich solutions such as FOAMINAL®, AFS, Advanced Pore Morphology (APM) foam and APM hybrid foam were considered. The design and cost analysis resulted in the use of sandwiches with a core layer of APM hybrid foam.

Figure 1: Battery pack (below) as an integral part of the BIW

Bild 1: Batteriegehäuse als integraler Bestandteil des Karosserie-Rohbaus

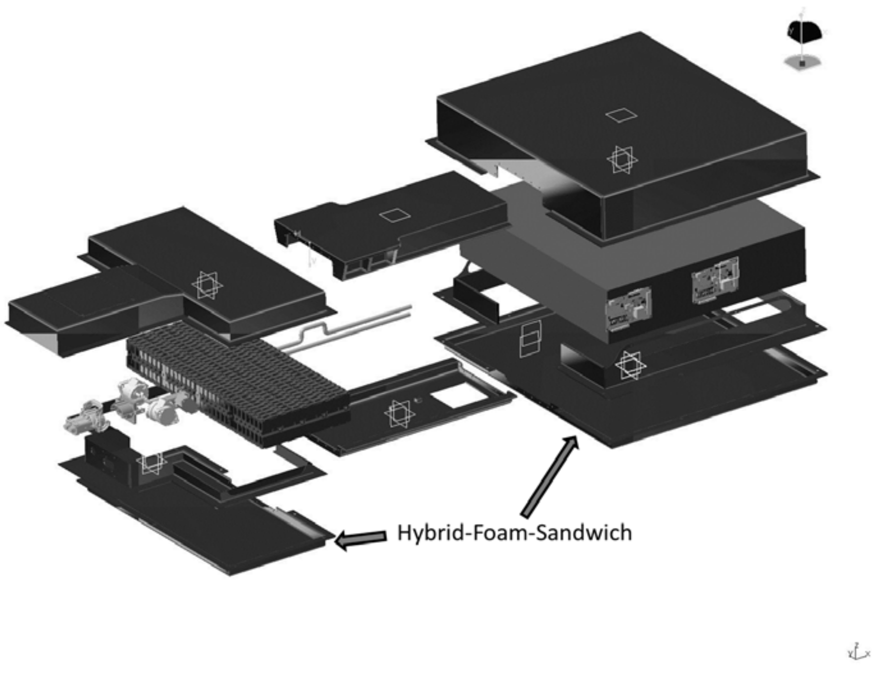


Figure 2: Design details of the battery pack and its housing

Bild 2: Design-Details des Akkumulators und des Gehäuses

2 Materials and processing

Basis for the production of sandwich structures with APM hybrid foam core layers is the so-called APM-technology [1-3]. This technology originated from the FOAMINAL® technology [4-5]. In the FOAMINAL® technology – a powder-metallurgical approach – metal (aluminium) powder is mixed with foaming agents like TiH_2 and compacted to a so-called “foamable precursor material”. Typical compacting methods are extrusion or uni-axial pressing – though other methods have been developed, too [6-7]. Subsequently, the precursor material is placed into moulds or into hollow metal components which shall be filled permanently with the metal foam. The moulds or the components are heated; the precursor melts, and fills the mould resp. component interior while expanding. Though this technology is well-established and has been used for a variety of commercial products it has several limitations. One drawback is the handling of the moulds limiting the productivity and increasing the costs. Furthermore, in the case of in-situ foaming in components the high process temperatures (about 700°C) might affect the structure and properties of the component material.

The main idea of the “APM-technology” is to divide the foaming process and the shaping process: in a first step precursor material is granulated resp. cut to small pieces which then are passing through a continuous belt furnace in which they are expanded to aluminium foam granules with diameters of 1mm up to 15mm. The surface tension of the molten aluminium, capillary forces, the internal expansion pressure and the original shape of the precursor pieces determine the shape of the granules which can range from globular to flattened or vermicular.

In subsequent steps the granules are coated with thermally activated adhesives and subsequently thermally bonded to larger structures, see Fig. 3. As the use of granules allows an easy control of pore structure the process is referred to as “Advanced Pore Morphology”. This technology offers eminent cost reduction potential in the case that hollow structures have to be filled as here no extra moulds (with extra costs) are necessary for the foam production. Furthermore, the foam granules can be prefabricated with reproducible and narrowly-defined material parameters.

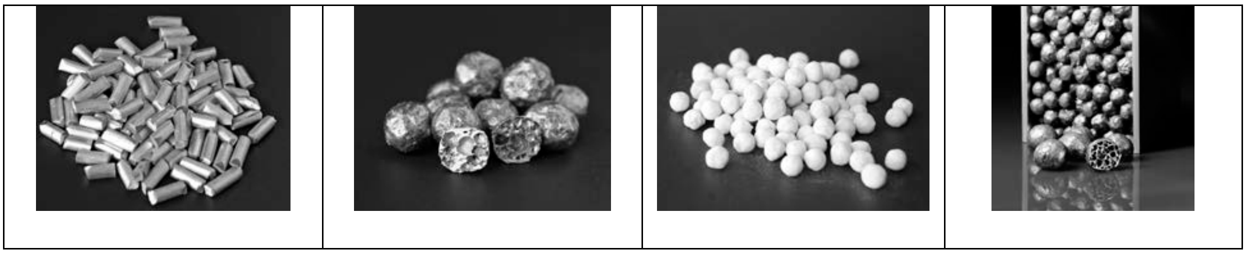


Figure 3: Process steps of the APM foam technology: cut precursor, foamed APM granules, APM coated with (foamable/non-foamable) polymer, filled hollow structure with cured conventional APM foam (from left).

Bild 3: Prozesskette der APM-Schaum-Technologie: granulierter schäumbarer Precursor, geschäumtes APM-Granulat, APM beschichtet mit aufschäumbarem Polymer, gefüllte Hohlstruktur mit integriertem APM-Granulat (von links).

In a modified approach such aluminium foam granules can also be used for the production of a new kind of hybrid aluminium-polymer foam where the granules are embedded into a matrix of polymer foam. In comparison to the conventional APM-technology the polymer coating contains in this case a chemical foaming agent. To produce a sandwich, the coated granules are poured between the two face sheets of the prospective sandwich structure. During a subsequent heat-treatment at moderate temperatures the adhesive melts, foams up and cures and bonds the aluminium spheres to each other and to the face sheets. The structure of a hybrid foam and a corresponding sandwich are shown in Fig. 4.

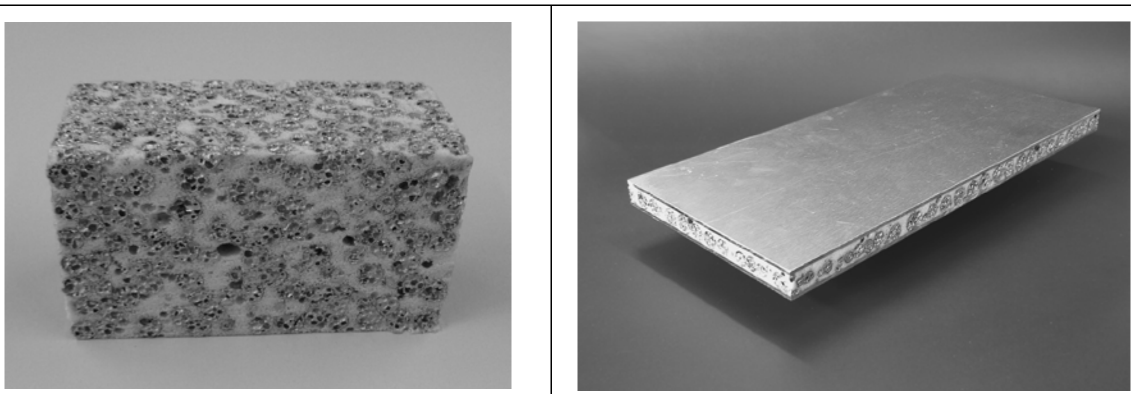


Figure 4: Left: APM hybrid foam structure, Right: sandwich with aluminium face sheets and hybrid foam core

Bild 4: Links: APM Hybridschaum-Struktur, rechts: Sandwich mit Aluminium-Decklagen und Hybridschaum-Kern

3 Material characterisation

3.1 Experimental approach

The mechanical properties of the core layer material were determined using cylindrical test specimens made from AlSi10 foam granules of diameter 7 mm but different real densities (0.55 g/cm^3, 0.65 g/cm^3, 0.75 g/cm^3) and two different coating thicknesses (100 μm and 200 μm, epoxy Araldite AT1-1 containing 1.5wt% Genitron OB as foaming agent). All test specimen were cured at 160°C for 3 hours in aluminium tubes, (Ø = 50 mm, h = 75 mm). For each set of parameters 3 samples were prepared and tested. For comparison also mono-epoxy foam specimens with varied density were produced in the same dimensions.

The quasi-static compression tests (following DIN 50106) were performed with a test unit Zwick 1476 with a test speed of 20 mm/min. The obtained stress-strain curves of the quasi-static tests were directly compared to the results of the high-rate compression tests, which are more relevant for typical crash situations. For the dynamic compression tests a fast driven servo-hydraulic high rate testing machine with a load capacity of 100 kN was used, see Fig. 5. The cylindrical specimens were tested at a velocity of 800 mm/s resulting in strain rates of approximately $10 s^{-1}$. The force was measured by a piezoelectric load cell. The elongation was determined via optical inspection with a special high speed video camera (up to 1 mio frames/s).

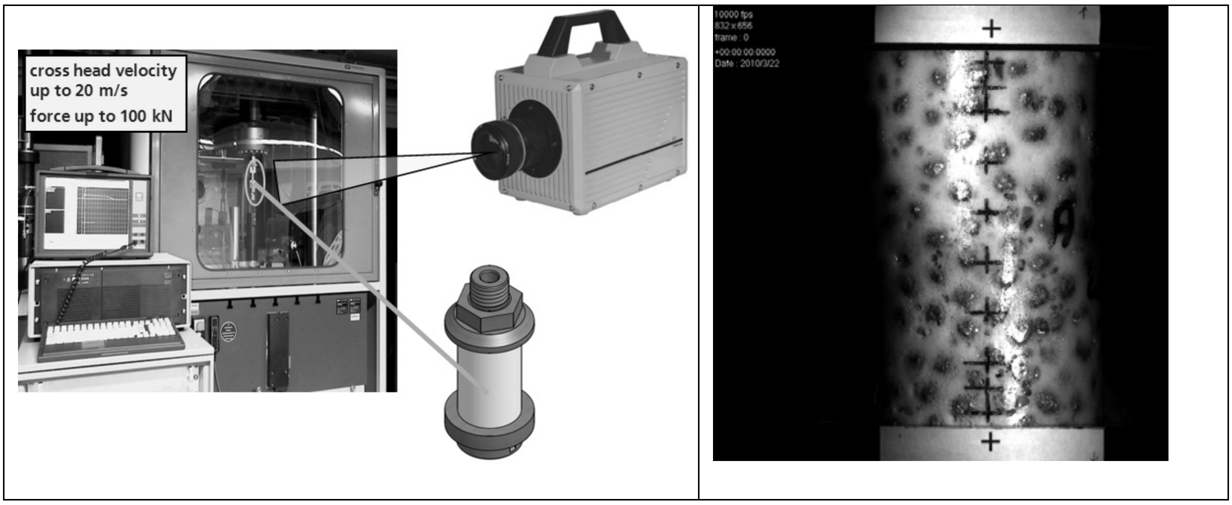


Figure 5: Setup for dynamic compression test at IWM, Freiburg

Bild 5: Aufbau des dynamischen Druckversuchs am IWM, Freiburg

3.2 Results and discussion

The compressive stress-strain curves obtained in the quasi-static and dynamic experiments for the specimens with 100 μm and 200 μm epoxy coating thickness are presented in Fig. 6 and Fig. 7. In all cases, the specimens showed the typical compressive material response of foams: an initial steep stress increase followed by a wide range stress plateau with almost constant stresses at increasing compressive strain levels. The final densification range was not covered by the dynamic experiments, since the evaluation of the experimental data is discontinued as soon as the strain rate decreases due to the commencing retardation of the loading device. For better comparison the quasi-static plots were limited to the same strain range.

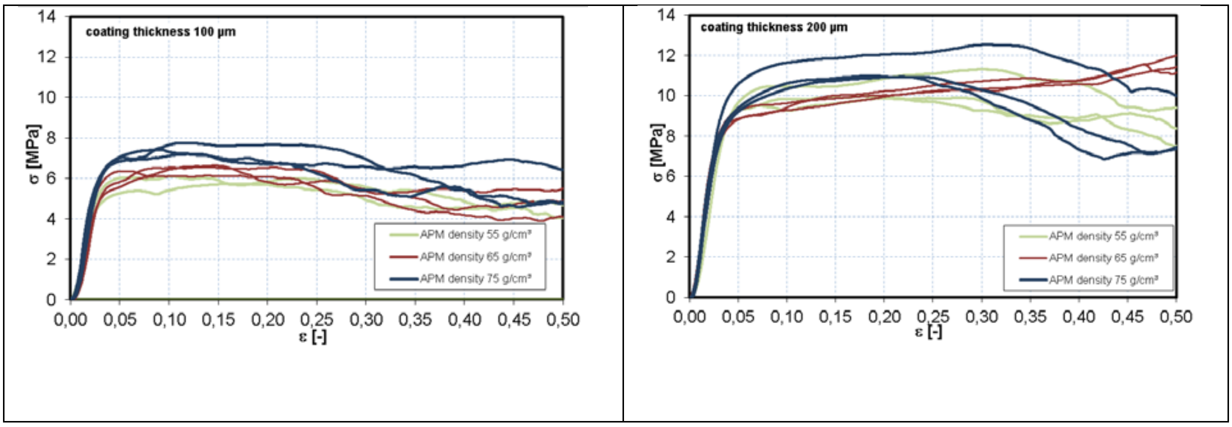


Figure 6: Compressive stress-strain response under quasi-static loading conditions (test velocity 20mm/min)

Bild 6: Spannungs-Dehnungs-Diagramme der Druckversuche unter quasi-statischen Bedingungen (Testgeschwindigkeit 20mm/min)

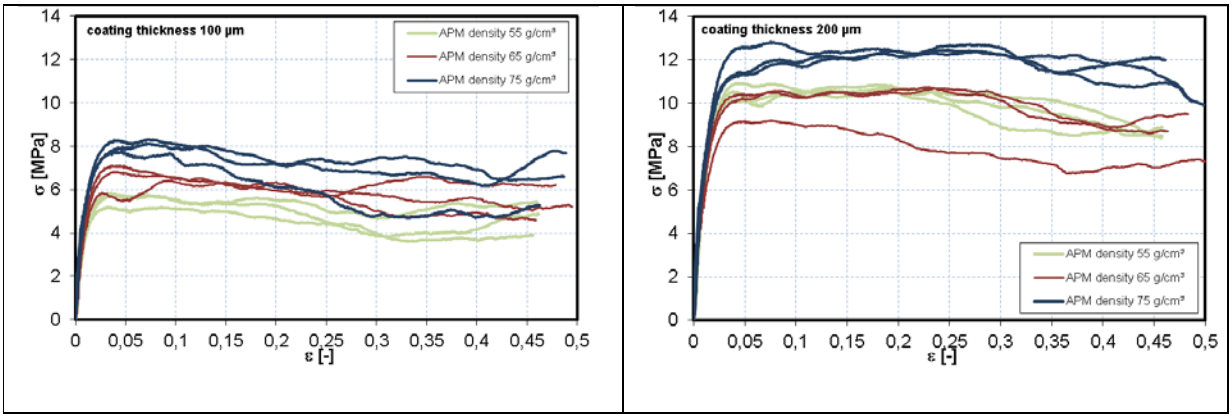


Figure 7: Compressive stress-strain response under dynamic loading conditions (test velocity 800 mm/s)

Bild 7: Spannungs-Dehnungs-Diagramme der Druckversuche unter dynamischen Bedingungen (Testgeschwindigkeit 800mm/min)

The comparison of the different material variants considered in this experimental investigation reveals that the plateau stress and thus the specific energy consumption increase with increasing APM density both for the quasi-static and high-strain-rate experiments. This increase can be simply explained by the higher amount of aluminum with higher yield stress in the hybrid material. Furthermore, it can be observed in Fig. 6 and Fig. 7 that increasing the coating thickness (from 100 µm to 200 µm) results in a higher plateau stress level. The influence of the polymer coating thickness on the resulting specimens' density and the plateau stresses (mean stress in the strain range of 20-40% [8]) is shown in Fig. 8 for the example of aluminium foam granules with a density of 0.65g/cm^3. The strong influence of the polymer on the deformation stresses of the composite foam can be explained by the high-strength nature of the Araldite AT1-1 polymer used in the investigation (see also Fig. 9).

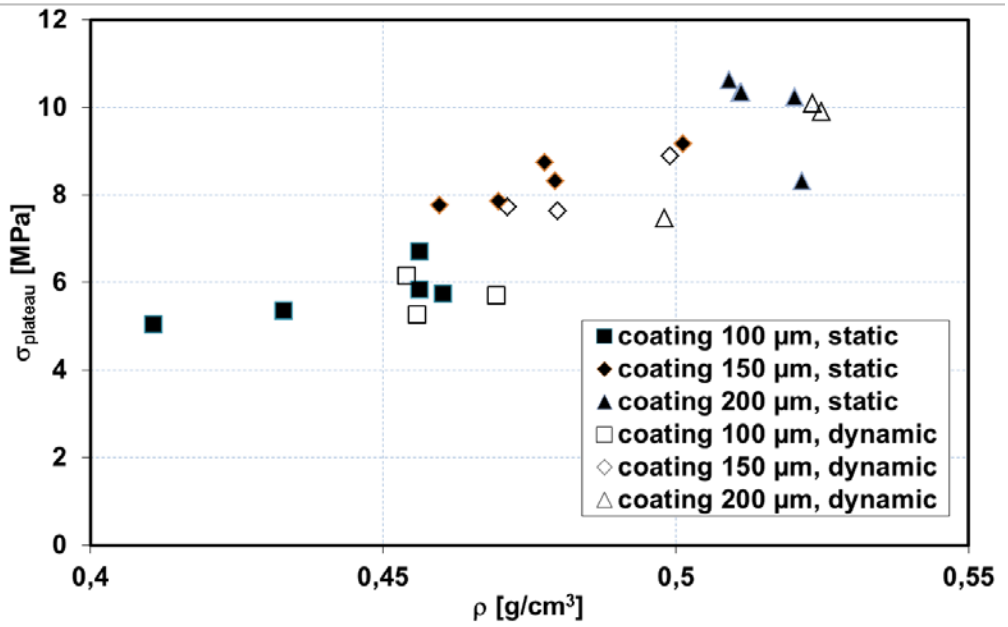


Figure 8: Dependence of plateau stress and density of the specimens on the polymer coating thickness (for 0.65g/cm^3-aluminium foam granules)

Bild 8: Abhängigkeit von Plateau-Spannung und Dichte der Proben von der Polymer-Beschichtungsdicke (Aluminiumschaum-Granulat mit Dichte 0.65g/cm^3)

Comparing the stress-strain-curves of the quasi-static and dynamic tests in Fig. 6 and Fig. 7 qualitatively no perceivable strain-rate effect can be found beyond the fluctuating range of the data. This is corroborated by the evaluation of the so called plateau stress as shown in Fig. 8 for the example of APM foam granules with a density of 0.65g/cm^3.

The observed absence of strain rate influence is in agreement to the behavior of aluminum mono-foams like Foaminal [9-10]. On the other hand Fig. 9 shows the plateau stresses of epoxy foams with different densities in quasi-static and dynamic compression. Obviously, in comparison to the hybrid foams the Araldite AT1-1 mono-foams exhibit a significant strain rate effect. The ratio of the quadratic interpolated quasi-static and dynamic plateau stresses is almost independent on the foam density and lies between 1.19 and 1.23 (see Tab. 2).

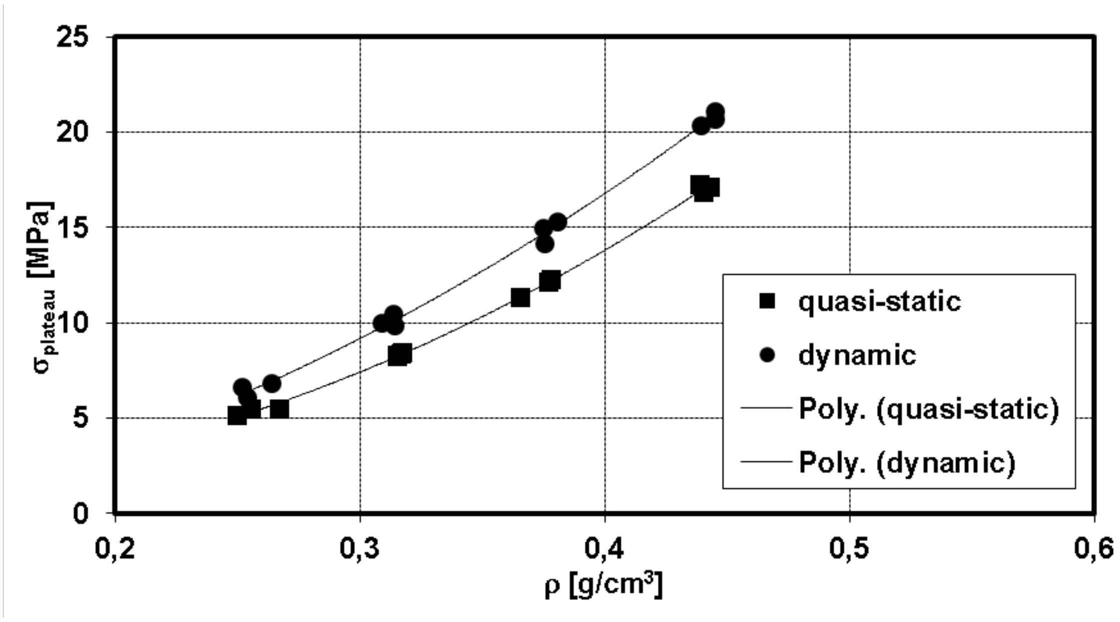


Figure 9: Plateau stresses of epoxy Araldite AT1-1 mono foams with different densities (quasi-static and dynamic compression tests)

Bild 9: Plateau-Spannung von Epoxy Araldite AT1-1 Mono-Schäumen mit verschiedenen Dichten (quasi-statische und dynamische Druckversuche)

Table 2. Ratio of the quadratic interpolated plateau stresses of quasi-static and dynamic compression tests in dependence on the density (epoxy mono-foams):

Tabelle 2. verhältnis der quadratisch interpolierten Plateau-Spannungen der quasi-statischen und dynamischen Druckversuche in Abhängigkeit der Probendichte (Epoxy Mono-Schäume):

Density	ratio of $\sigma_{plateau}$ (dynamic/quasi-static)

[g/cm^3]	
0.25	1.21
0.30	1.23
0.35	1.23
0.40	1.21
0.45	1.19

One could expect that the significant strain rate dependency of the polymer foam matrix should also reflect to some extend in the behaviour of the hybrid foams. That this is not the case can be attributed to the complex mechanical interaction of the metal and polymer foam phases of the hybrid material. Though no detailed analysis is available so far some qualitative explanation can be found in the observation of a more brittle behavior of the hybrid foam in comparison to the polymer mono-foam. Especially for the dynamic compression tests this can lead to spalling of material combined with material and, therefore, strength loss of the test specimens.

The disadvantage of the slightly inferior ductility of the hybrid material is compensated by several advantages; there can be mentioned lower costs and easier process control. Process control is especially difficult for the production of larger foam volumes of epoxy-mono-foams because the incurring exothermic curing heat in combination with very low heat conductivity can induce the degeneration and destruction of the foam structure in the component’s interior. Combining epoxy and polymer foam will lead both to a significant reduction of the curing heat and an improvement of the internal thermal transport. Large foam components can be produced this way, see the example in Fig. 10.

Figure 10: Example of a large epoxy-aluminium hybrid foam block (after machining)

Bild 10: Beispiel eines großen, aus Epoxy-Aluminium-Hybridschaum gefertigten Würfels (nach mechanischer Bearbeitung)

4 Battery housing prototype

After the determination of the mechanical properties of the core layer material the detailed parameters of the sandwiches for the bottom parts of the battery housing were calculated. These parts have the shape of rectangular pans with flanges; see Figure 11, with only the pan base designed as sandwich with hybrid foam core. In a serial production scenario the pan-like face sheets could be produced by deep drawing. For the prototypes of the “SmartBatt” project the face sheets were manufactured by bending the rims of flat aluminum sheets and welding the edges.

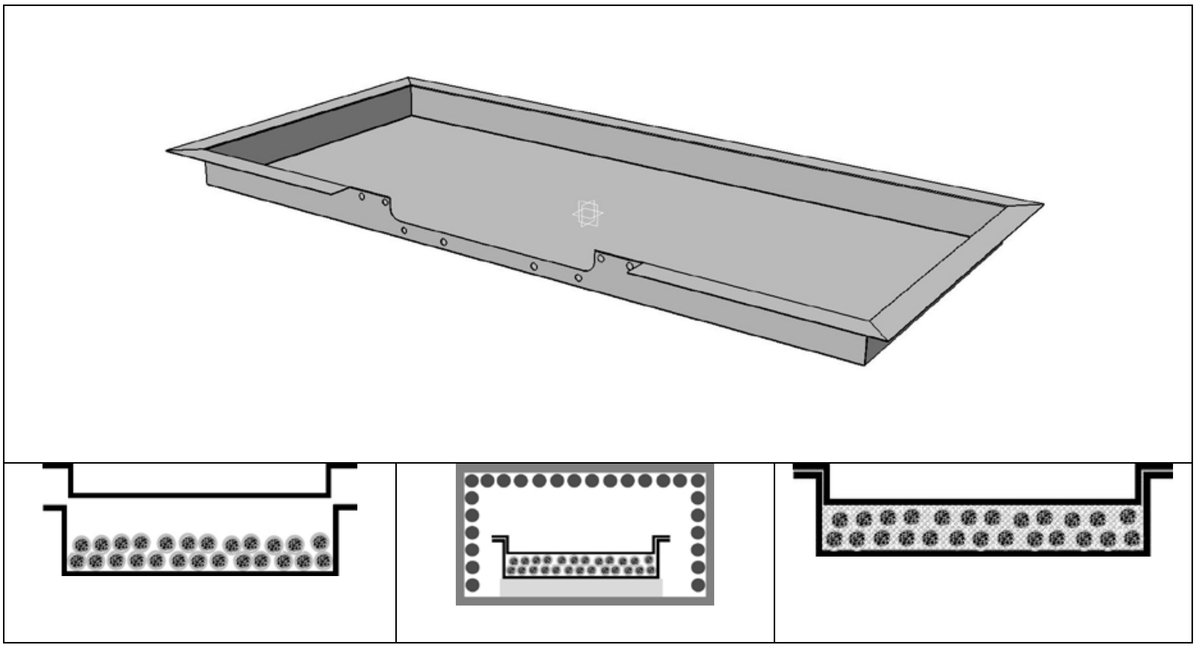
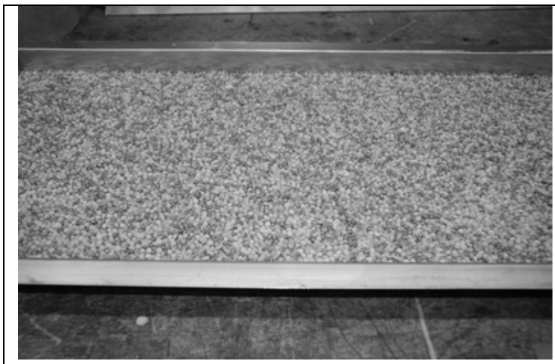


Figure 11: Above: CAD drawing of the bottom part of the SmartBatt battery housing, below: Schematic depiction of the production of the bottom parts of the battery housing: separate pan-like face sheets with filling of coated APM granules, curing of the closed sheets, final component with local sandwich structure (from left)

Bild 11: Oben: CAD-Zeichnung des Untersegments des SmartBatt-Batteriegehäuses, untere Reihe: Schematische Darstellung der Herstellung des Untersegments des Gehäuses: separate wannenförmige Deckblech-Strukturen, gefüllt mit beschichtetem APM-Granulat, Aushärtung der geschlossenen Struktur, finales Bauteil mit lokaler Sandwichstruktur (von links)

Limited construction space and the high strength and stiffness of the APM hybrid foam sandwiches resulted in a total sandwich thickness of only 5 mm. Therefore, aluminum spheres with a diameter of 4 mm and a face sheet thickness of 0.5 mm were selected. Granules cut off from an AlSi10 precursor wire were foamed up to a real density of 0.6 g/cm^3, so that a bulk density of 0.4 g/cm^3 was obtained. The foamed spheres were coated with the epoxy Araldite AT1-1 containing 1.5wt% Genitron OB as foaming agent (bulk density of the coated spheres: 0.46 g/cm^3). For manufacturing the prototype sandwich pans a first pan – representing the bottom face sheet – was filled with a monolayer of coated APM spheres. Then a slightly smaller pan – representing upper face sheet – was inserted into the bottom pan so that both face sheets were in direct contact with the monolayer of spheres. To achieve a bonding of the flanges the inner parts of the flanges were coated with the same adhesive (Araldite AT1-1), but without a foaming agent. Foaming and curing of the adhesive coating was accomplished by heating the composed pan in a furnace at 160°C for 3 hours. After this heat treatment all aluminum spheres were bonded to each other and to the face sheets and also the flanges were glued together. The result of the process is a 3-dimensional component which combines hybrid foam sandwich structures with compact aluminium outer rims. 2 of those sandwich components were subsequently fastend with several other components made from aluminium and integrated into the whole battery housing system (Fig. 13).



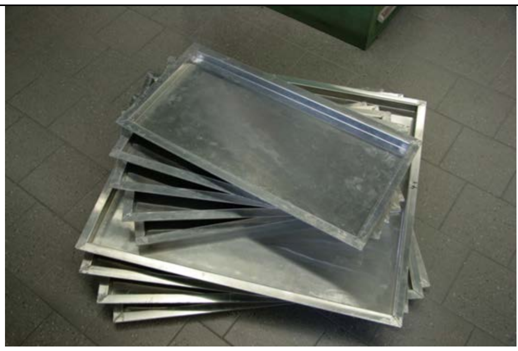


Figure 12: Left: Lower face sheet with APM-granules filling, Right: finished bottom housing parts of front and rear battery pack

Bild 12: Links: Untere Decklage mit APM-Granulatfüllung, rechts: finalisierte Bodenstrukturen des vorderen und hinteren Batteriepakets

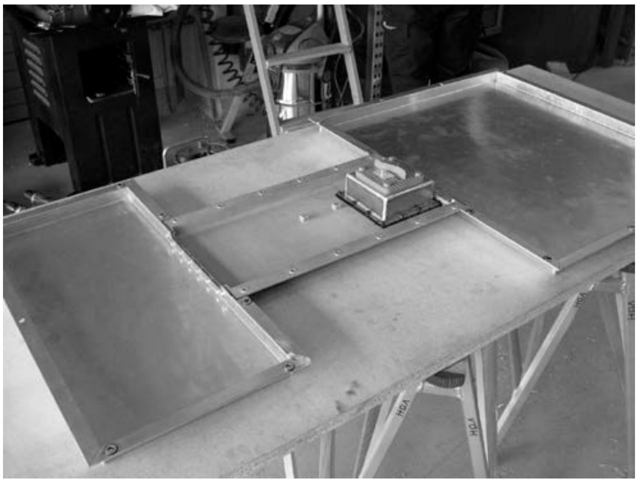


Figure 13: Assembled lower structure of the battery housing including two sandwich components with hybrid foam core (left and right parts)

Bild 13: Zusammengebaute Bodenstruktur des Gesamt-Batteriegehäuses einschließlich zweier Sandwich-Bauteile mit Hybridschaum-Kernlage (links und rechts im Bild)

The integral density of this 5 mm sandwich material is 0.94 g/cm^3 – one third of the density of compact aluminum (2.7 g/cm^3). The bending stiffness was calculated to be $3.54 \cdot 10^8$ Nmm^2, the measured weight per unit area was 4.72 kg/m^2. This can be compared to a monolithic aluminum sheet of 3.3 mm thickness which has a bending stiffness of only $2.1 \cdot 10^8$ Nmm^2 (57% less) and a mass of 8.91 kg/m^2 (89% more).

Due to the thickness and good energy absorbing properties of the aluminum foam sandwich material also an enhanced intrusion protection was realized. In addition the thermal properties of this material are another benefit. Measurements of the coefficient of thermal conductivity of the APM hybrid foam sandwich material resulted in a value of 0.4 W/(m•K) [5], which is more than 500 times lower than the coefficient of thermal conductivity of solid aluminum (220 W/(m•K)). This also indicates an enhanced protection of the battery modules in case of an accident involving fire.

In comparison to other sandwich structures the main advantages of the sandwiches with hybrid polymer-aluminium core can be seen in

- facilitated manufacturing procedures
- enlarged design possibilities (combination with non-sandwich areas, in this example case the flanges)
- a good combination of high specific stiffness, intrusion resistance and crash energy absorption abilities and
- an isotropic mechanical behaviour of the core layer.

In comparison to sandwiches with aluminium mono-foam core layers ("aluminium foam sandwiches - AFS") the main advantages can be found in the significantly enlarged freedom of design and freedom to choose face sheet alloys.

The new battery housing design was subsequently evaluated for the selected example system of a purely electric vehicle with a driving range of >120km (with a 23kWh battery). State of the art is an energy density of the battery including housing of 80Wh/kg (e.g. Nissan Leaf). In comparison to this with the new design an energy density of 148 Wh/kg could be obtained. Crash tests and computer simulations showed that this improvement of energy density was not done at the expense of safety. The crash behaviour of the new battery housing design concurs and even excels those of the SuperLightCar (SLC) concept with internal combustion machine.

5 Conclusion

In the European research project “SmartBatt” it could be shown that innovative materials (aluminum hybrid foam) and intelligent mechanical engineering can significantly increase the energy density of battery packs for pure electric vehicles. A main item of the improved design is the application of pan-shaped bottom parts of the battery housing. Because of the selected production method these components can easily combine hybrid foam sandwich structures with compact aluminum leading to improved specific stiffness and intrusion protection. Sandwich structures with hybrid aluminium-polymer foam cores constitute, therefore, an interesting addition of the existing range of commercially available sandwich materials. Future work will address the further deepening of the fundamental understanding of the mechanical material behavior as well as the extension of the variety of polymer foams combined with the aluminium foam granules.

5 Acknowledgements

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