OPPORTUNITIES FOR COMPOSITE MATERIAL IN FUTURE MULTI-MATERIAL BATTERY ENCLOSURES

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Abstract

In a consortium project with 46 participating companies, AZL has investigated a large amount of alternative multi-material solutions for a state-of-the-art welded aluminum battery casing. Alternative materials included both thermoset and thermoplastic materials, solid laminate or sandwich solutions, short fiber overmolded solutions, various SMC options, steel, aluminum, and combinations of all these materials. All relevant load cases were considered in the CAE analysis, as defined by safety regulations, in combination with specific OEM requirements. In total 20 different multi-material concepts were optimized on weight and cost and compared to the aluminum reference component. All production steps were cost-modelled in detail to obtain reliable cost estimates for each variant. As a result, each concept resulted in different weight savings up to 36%, and cost savings up to approximately 20%, with respect to the aluminum reference.

Due to new requirements on fire resistance during thermal runaway, experimental fire testing on different materials and protective layers, is currently being performed. This testing includes measurement of material strength under fire loading. Next to this, high-speed foreign object bottom penetration resistance of various material solutions is also being tested, to better estimate protection levels for future battery pack layouts as e.g. cell-to-pack.

Introduction

Electrical cars are the future. To combat climate change, governments worldwide take many measures to reduce CO_2 emissions, and one of them is stimulating the use of electric passenger vehicles, to replace vehicles with internal combustion engines. Most market studies predict a strong increase for battery electric vehicles (BEV) over other types, see example in figure 1, showing the global yearly sales predictions for passenger vehicles.

In this example the trends are just based on technology and economic developments, and not on any optional policies to achieve carbon neutrality in 2025. Note that there is quite a regional difference in adoption of electric vehicles, where Europe and China are leading with nearly 60% EV sales in 2030. Also note that the European commission has recently proposed that in 2035 100% of the sold passenger cars and vans must be zero emission vehicles.

It is also predicted that fuel cell or hydrogen powered vehicles will have only one or two percent market share. One of the reasons for that is, that in the total chain from well to wheel the energy efficiency of battery vehicles is much better than for hydrogen/fuel-cell vehicles, as shown in figure 2. This makes that on the same amount of sustainable generated electricity, a battery electric vehicle can drive significantly more distance, making it not only cost-attractive for the end-user but also a preferred way for the time period when sustainable energy supply is still limited. Still there will be situations that hydrogen has its advantages, as e.g. in the case of long distance trucks or aircraft.

The conclusion is that in future the vast majority of the passenger cars will be of the BEV type. There is however also a disadvantage to this, being that batteries are heavy, order of magnitude 500 kg for an average battery pack, from which about 100 kg may be the battery pack casing structure. In comparison, an average steel body in white (BIW) structure weighs only 300 kg. To increase range, but also to lighten other chassis and car components, weight saving is highly desired, but typically at no cost increase. This makes it valid to investigate whether composite materials can play a role in various multi-material options for a battery casing. This was done in a multi-partner research project at AZL with 46 participating companies along the complete value chain. Some interesting results of this project are presented in this paper.

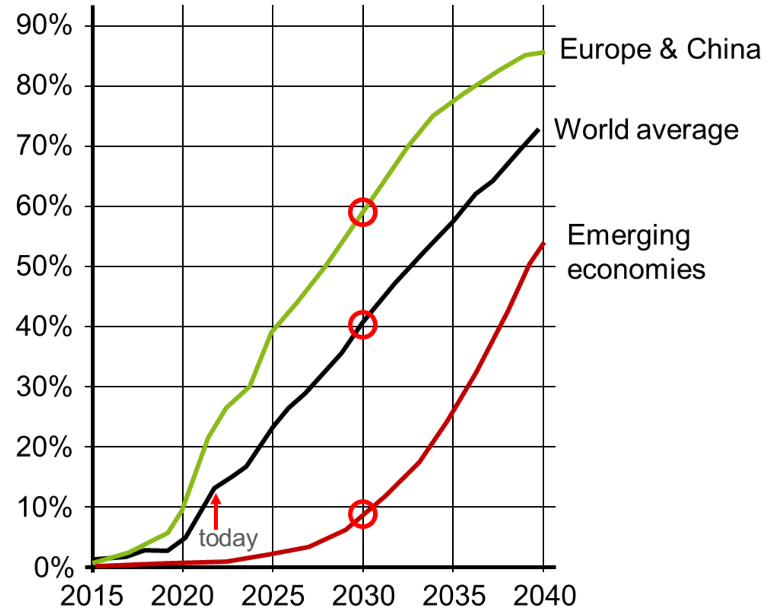

Figure 1: Market prediction for electric vehicle (BEV and PHEV), sales percentages by BloombergNEF [1]

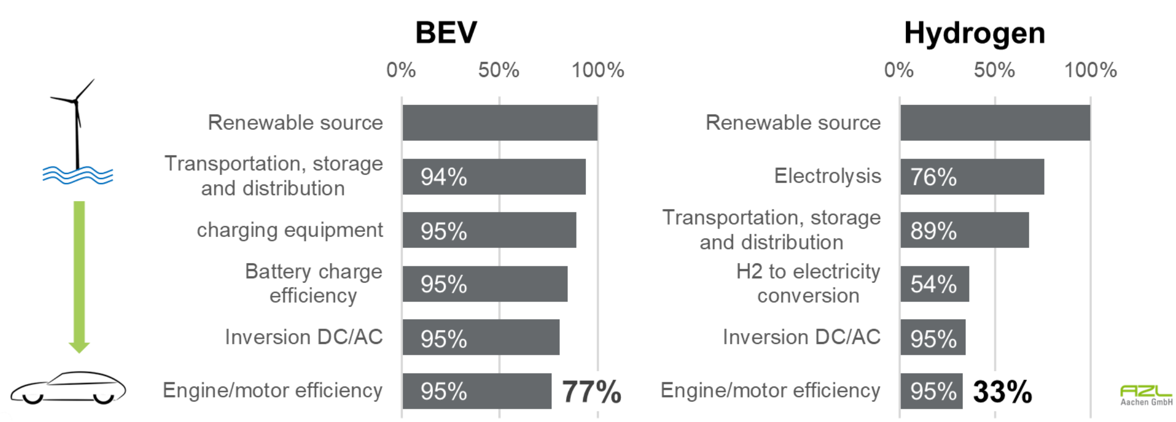

Figure 2:Comparison of Battery and Hydrogen EV efficiency from well to wheel. Efficiency values per step in white, overall efficiency value in black. Future 2050 efficiencies expected to improve to 81% for BEV and 42% for Hydrogen. Data used from [2]

Multi-material battery casing project, design methodology

At AZL the project on designing many multiple material concepts was carried out in different phases:

1. Background information collection and analysis
    - Analysis of 40 existing series production casings and concepts
    - Analysis of standards, test methods and requirements for battery casings
2. Definition of a reference component: To compare new alternative material solutions on cost and weight, a generic aluminum reference casing was designed
3. Design and CAE analysis of 20 different multi-material concepts
4. Definition of production chain and cost analysis for these concepts

This paper will focus on the design methodology and the cost and weight results for each concept.

To be able to compare many different multi-material options on cost and weight with state-of-the-art alternatives, it was decided to also design a generic aluminum reference component, to make the results not specific to one specific car model. Also, in this way, more honest weight and cost comparisons can be made, as both new multi-material concepts and the generic state of the art concept were CAE analyzed and optimized to the same performance requirements. The reference component was agreed with the consortium to be designed, following a typical layout for a mid-size car (suitable for about 70 kWh battery), where the box is constructed from welded aluminum alloy profiles and sheet material. In this case also a separate aluminum sheet metal bottom protection plate and lid were part of the total casing structure, see figure 3. The dimensions, material thicknesses and alloy type were chosen after consultation with a major German OEM and expert talks. Note that for comparability reasons, the box outer dimensions were fixed to define the same design space for each multi-material concept.

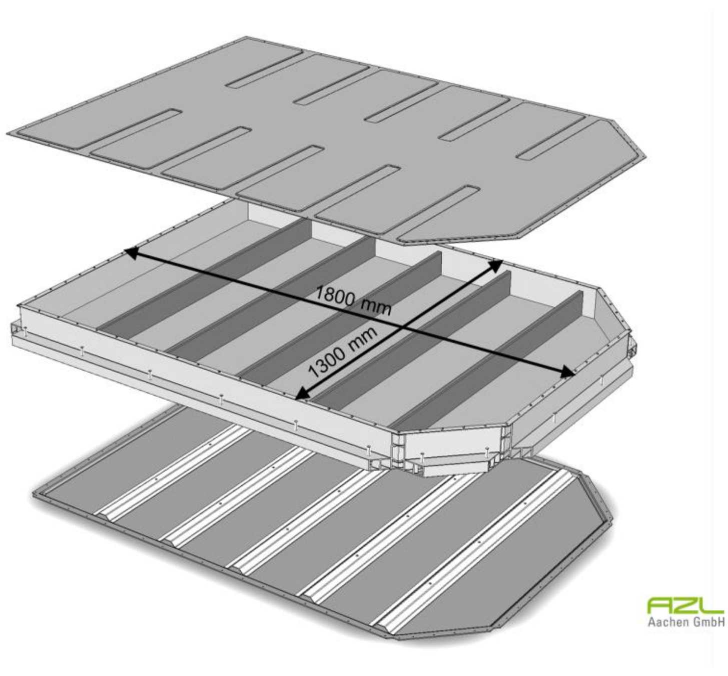

Figure 3:Aluminum reference component, welded box structure, bottom protection plate and lid.

Next this aluminum casing was analyzed on the most important load cases, to define a reference level of stiffness or safety, that had to be at least equal for the newly developed multi-material concepts.

Mechanical load cases considered were:

- Pole intrusion according to GB38031-2020
- Bollard intrusion to the bottom of the car, an OEM specific test
- Deflection under own weight and g-loads, including 400 kg of battery modules
- Stiffness of the lid under own weight (vibration), and strength due to overpressure, resulting from thermal runaway gasses.
- Crash shock loads in x- and y-direction

Non mechanical requirements were added for the non-metallic concept designs to comply with:

- Bonfire test according GB38031-2020
- Thermal runaway according GB38031-2020
- Electromagnetic interference shielding (EMI), OEM specific requirements.

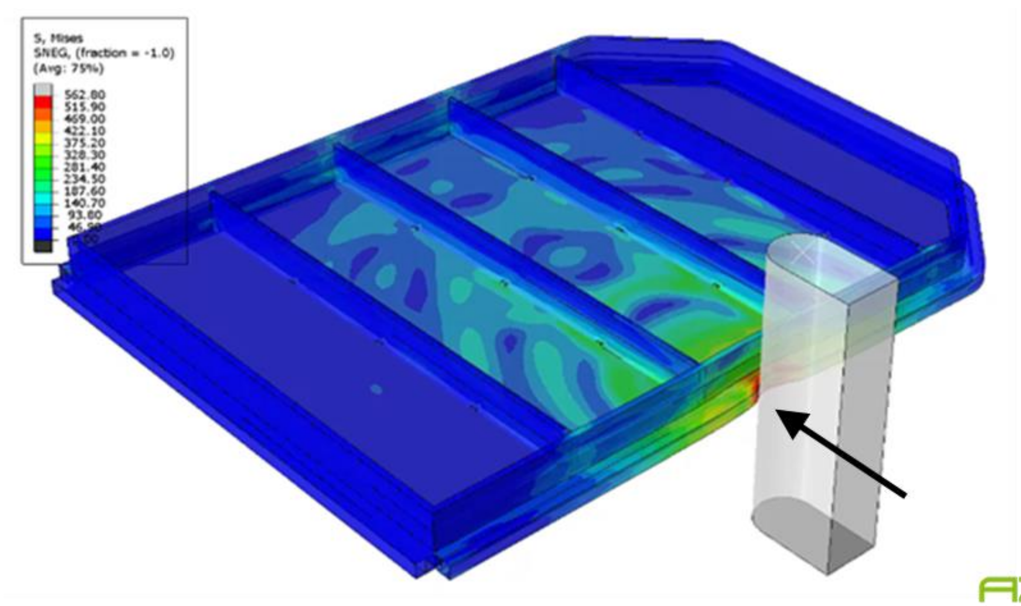

Figure 4: Pole intrusion CAE simulation.

Note that the pole intrusion was always calculated both at a position in line with the internal cross beams, and just in between the middle of both beams, as depicted in figure 4. Although the relevance may be questionable, the pole intrusion was also checked on the short side in x-direction (driving direction). GB38031-2020 (and derived international standards) says that the test should be continued until 1/3 of the width has been intruded, or 100kN has been reached. Simulations on all concepts, and data from literature, showed that for all concepts the 100kN level is reached first. Note that in consultation with the OEM in this project a large safety factor was added to this 100kN requirement. For the alternative material concepts, this same higher load was taken, and the designs were made such that equal safety was obtained, practically meaning same or lower intrusion levels into the battery module compartments. An important observation is that this load case is actually a static strength load case and does not require a certain amount of energy absorption.

Besides the pole intrusion, also another very demanding load case was considered, called the bollard intrusion. This is about a large pole pushing into the bottom of the battery box assembly, and even able to lift the complete car upward via the battery box. This bollard intrusion can be located at any position, and simulations showed that a position midway between cross-beams is most critical. This is illustrated in figure 5.

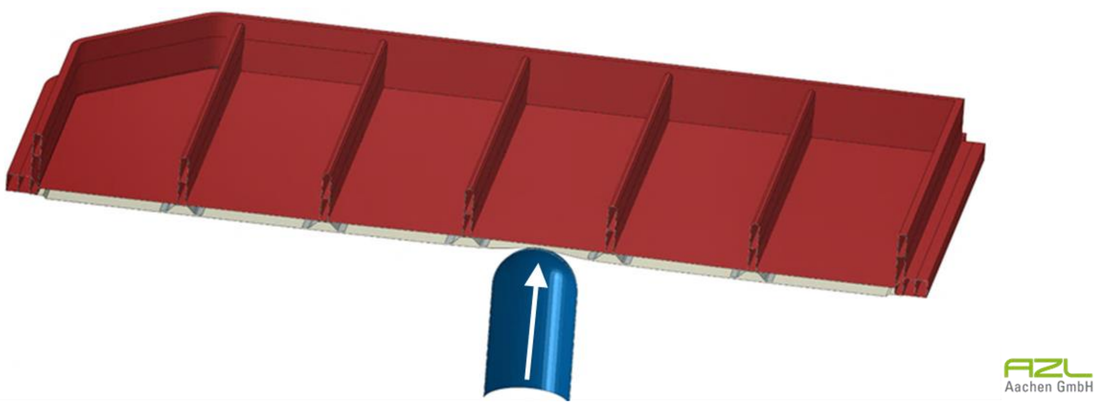

Figure 5:Bollard intrusion. Right half of box shown. Most unfavourable bollard position in between cross beams. Bottom protection plate is deformed while lifting the car upwards.

The criterium here is that no damage would result to the cooling system, typically located below the batteries. Or at an even higher level of intrusion, no damage to the batteries. All alternative material concept designs were dimensioned to have at least equal reaction forces at typical intrusion levels until damage could be expected. In the case of the aluminum reference casing this was set to about 20kN at 20mm intrusion.

Other load cases included same stiffness as the reference box. E.g. same deflection under the weight of batteries, also at higher acceleration levels. And same stiffness of the lid under its own weight to be equally resistant against vibrations. For the lid also the overpressure case was considered that would follow from gas release during a thermal runaway.

Further the effects of 90g crash shock pulses were checked, but it was found that this load case actually only would mainly cause stress peaks a the battery casing to body in white bolted connections. So this case would not drive the alternative material designs that much.

Alternative multi-material concept designs

When looking at alternative material design concepts, potential variations are unlimited. We tried to look for application of all potential relevant material types, being:

Metals:

- Aluminum (sheet and extrusion)
- Steel

Thermoset:

- SMC in various types:
  - Standard SMC
  - High modulus SMC (glass fiber based)
  - Carbon SMC
- Prepregs
- Hybrids from SMC and prepregs
- Pultrusions

Thermoplastic:

- Injection molding resins, LFT's
- UD tapes
- Laminates (Organosheets)
- Pultrusions

Sandwich core materials:

- Honeycomb
- Foam

Where it made sense, material solutions were also mixed to have different materials for different sub-components.

Then we also looked at different manufacturing routes, typically more focusing on mass production, like press forming, injection molding, but also innovative techniques like thermoplastic sheet or sandwich folding.

Finally, about 8 design families were developed, see figure 6, were within each design family, material choices were varied, and CAE optimization analysis were performed to find the lightest possible designs.

Some components could be considered individual in the optimization process such as the lid, which could be applied to many different box concepts. The same applies to the bottom protection plate.

To illustrate how different materials were evaluated, as a first example, consider the lid as displayed in figure 3. In this case we looked at the effect of both geometry changes (within the available design space) and material variants. As a first step, just a topography optimization was performed to just see what would be achievable in the same aluminum material by just changing the geometry. The result is shown in figure 7.

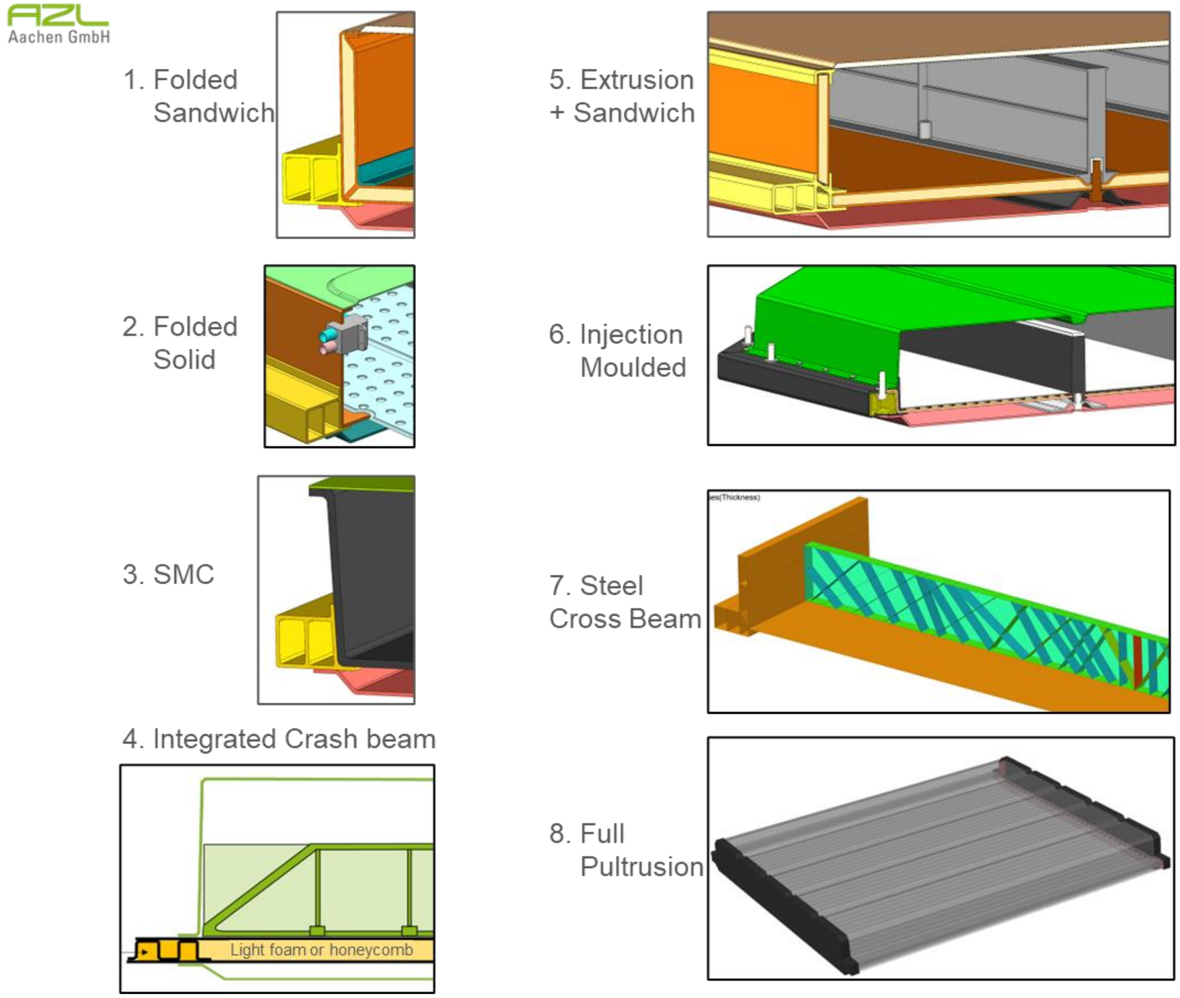

Figure 6: Various design concept families. Pictures show some typical details

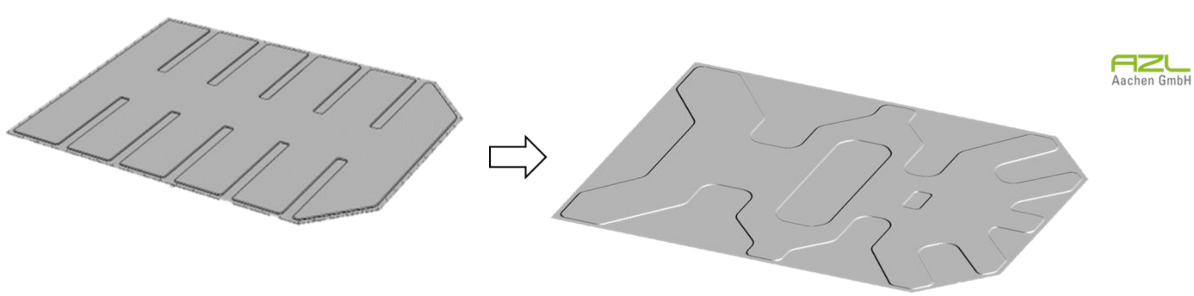

Figure 7:Topography optimization on lid. Optimized part is 30% lighter.

Note that in this case the lid is only fixed around the perimeter, without extra mid fixation points. For comparison of different materials or geometries this doesn't matter, as all variants are compared on the same boundary conditions and same loads and stiffness performance. However, different materials may allow different geometries. As an example, long bead stiffeners as present on the original aluminum reference lid, may need some significant radii to allow press forming without cracking the aluminum, while SMC or injection moldable materials will allow much sharper corners to be formed. The result of this is that bead stiffeners can actually be designed much deeper (or higher) in these materials, and thus providing more geometrical stiffness. Also at the same time, when clever designing such stiffeners, they will even allow more space for battery modules at the same total pack height. This is explained in figure 8. Bead stiffeners with sharp corners could be quite high in a narrow space between adjacent battery modules, typically separated by a cross beam structure. Then at the same time at a given maximum pack height it will give maximum space for the battery modules.

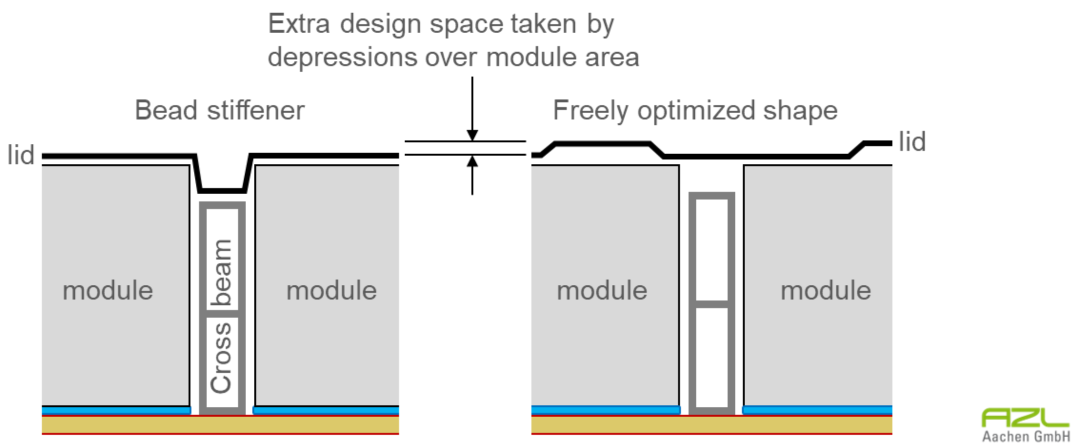

Figure 8:Cross-sections: Materials allowing sharp stiffener corners (left) may save on design space over shapes that have depression over battery modules (right).

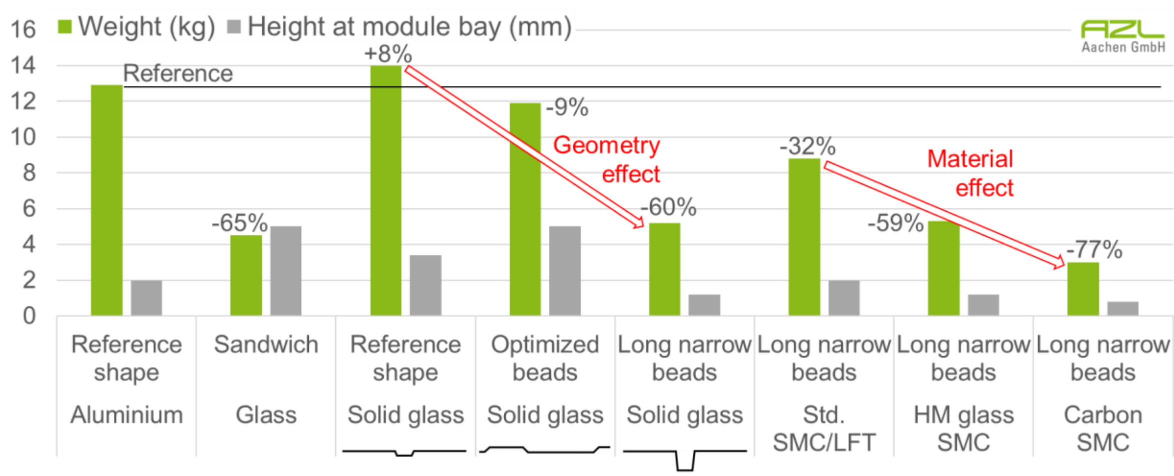

Figure 9:Lid weight and design height comparison for different materials and geometries. Glass = glass fabric or cross-ply UD laminate, std.SMC/LFT is either standard glass fiber SMC or injection molded SMC. HM=High Modulus, high fiber volume SMC

The effect of choosing the right alternative geometries on weight saving is much higher than using high modulus materials. As explained in figure 9, for the same glass composite material, deep bead stiffeners can reduce the weight of a lid from 14 to 5 kg, while maintaining the same stiffness. High modulus materials will also reduce the weight, but typically at an extra cost. For relative flat components, such as the lid, a sandwich solution can also be very light, as showing in figure 9. However, it will take a few millimeters extra height, that in turn will reduce the available space for battery modules at a given battery pack design space below the car.

Just as an example some details for two design families will be shown:

- An SMC box variant
- An injection overmolded variant

The SMC variant is shown in figure 10 below. Advantage of this concept is that the box structure will be press formed in one operation, while providing details for easy positioning of the cross beams and simultaneously providing mounting hole provisions. The casing structure was analyzed with aluminum extruded cross-beams, but also with injection overmolded beams, each option giving different solutions to e.g. mounting bottom protection plates, or gluing the cross-beams in place. For the latter process the injection overmolded cross-beams would have some advantages in easier glue application. The SMC material further gives the advantage that the box bottom and side walls may be optimized each to different thicknesses, of course within the boundaries of the processibility of the material. CAE analysis results showed that the wall thicknesses, especially at the bottom would become quite thick, 7 mm for a standard SMC material. Therefore, also hybrid variants were analyzed were fabric prepreg materials are combined with the standard SMC in one press forming operation. A significant weight saving could be obtained this way, and even more, when also the side walls would be a hybrid material layup. In that way the molded box-component weight could be reduced from 41 to 32 kg, at only a slight cost increase.

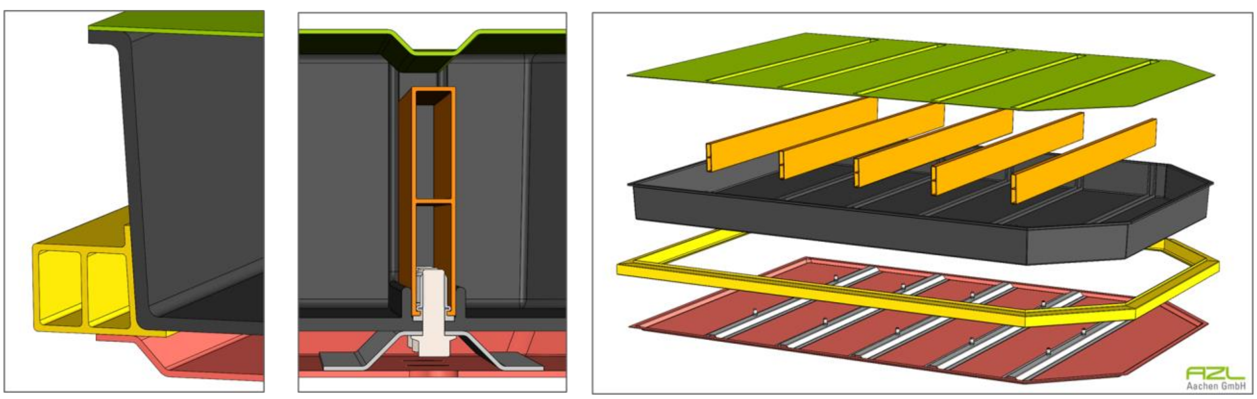

Figure 10: Cross-section details and exploded view of an SMC box variant. Bottom protection plate, edge profiles and cross beams are aluminum, box is SMC, lid is solid laminate.

The injection overmolded variant is shown in figure 11. In this case again an aluminum extrusion edge protection profile is used, which is fully overmolded with LFT (Long Fiber Thermoplastic) compound. At the same time, the bottom of the box is formed from a continuous fiber thermoplastic composite laminate, which is formed into shape during closing of the injection mold. In this case also flow channels for cooling fluid are overmolded on the bottom laminate. In a second operation aluminum sheets are welded to these flow channel ridges to form a closed integrated cooling plate structure. Similarly on the top of the high cross-beam ribs aluminum strips are welded to form a strong and stiff cross beam structure. For this welding operation the aluminum plates and strips should be pre-treated to achieve a strong connection, e.g. by chemical or laser surface structuring or by applying an overmolding resin compatible coating, such as already exists as a commercial product.

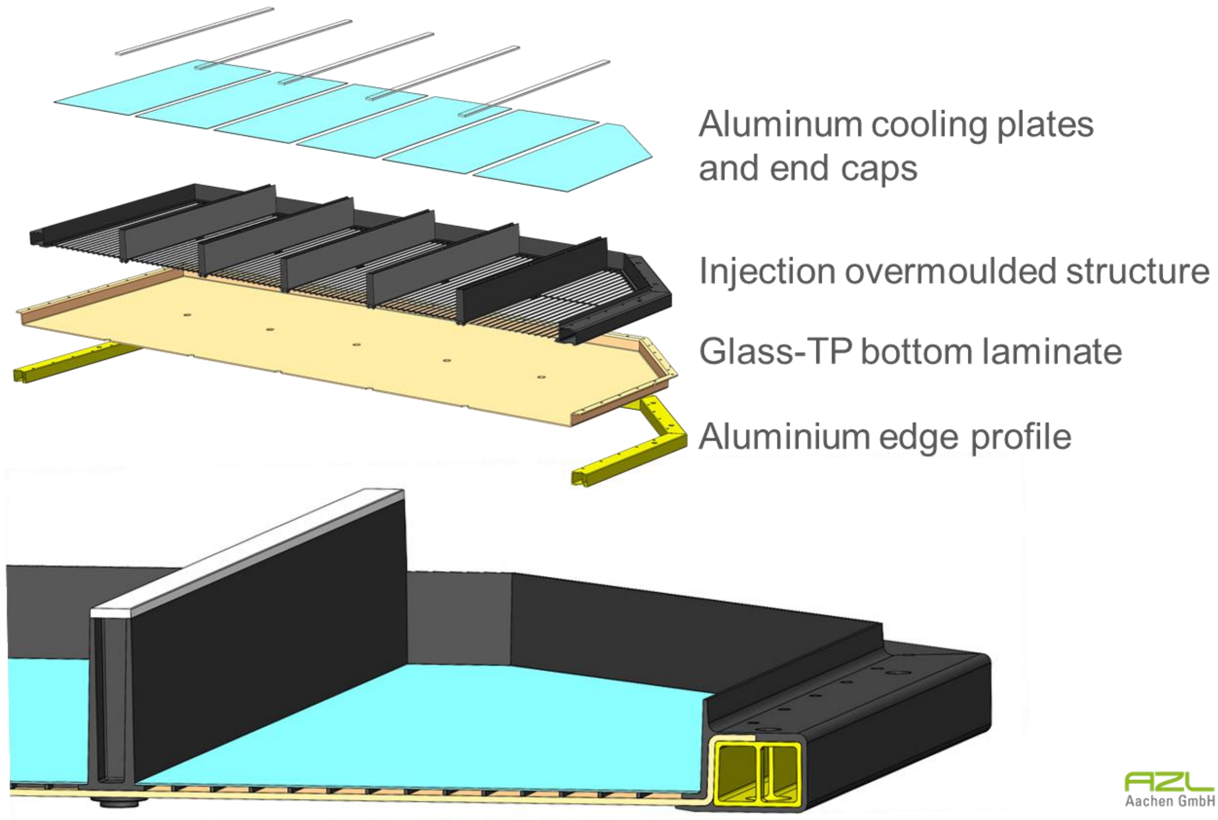

Figure 11: Injection overmolded concept detail and exploded view (left half of casing, lid and protection plate not shown here)

It is to be noted that although the project surface area of the box is large, the required machine clamp force will still be limited, as the project area of the injection molded resin is still relatively small, while the thermoplastic laminate forming the box bottom doesn't need that high clamp forces.

For each design also solutions were developed to comply with EMI (Electro Magnetic Interference) shielding, such as e.g. simple application of aluminum foils, or alternatively using aluminum coated glass fibers as an integral layer in a composite layup.

To make a multi-material battery casing fire resistant, various options were listed. Note that the state-of-the-art aluminum reference casing would comply with a Bonfire test but would fail during a thermal runaway test. Only recently OEMs started to design casings for this internal fire load case. As various solutions are currently still under investigation, the weight and cost for these protection methods was not included in the comparison of concepts. However, it is expected that composites will compare favorably in comparison with aluminum, as e.g. already a 5 minute thermal runaway flame exposure will melt a hole in aluminum quite quickly, while long or continuous fiber material will survive much better. Better comparisons between materials will soon be available as result of another AZL multi-partner project, where many different material and protection layer solutions are tested in an application relevant test set-up.

Weight and cost for different multi-material variants

Each concept variant was optimized for minimum weight, while providing equal performance and safety compared to the aluminum reference part. Then the production process was modelled in detail using the Oplysis software from company Conbility. Material cost, production cost and investments were taken into account. The cost calculations for composite components were based on the vast AZL experience. For the metal components the expertise of the metal production institute WZL in Aachen was additionally included. Finally for each concept the cost structure was calculated with a scatter band, taking into account e.g. variations in material price. An overview of the cost and weight of most variants is given in figure 12. Note that many concepts, both in thermoset and thermoplastic material are cheaper than the aluminum reference part. This has partly to do with the high cost of aluminum, such as in the form of extrusions, while glass fibers are still relatively cheap. The lightest concepts in this graph are locally containing carbon fiber material, but they can also be more expensive than the aluminum part.

The graph also shows a line that shows equal attractiveness when a kilogram of weight saving would be valued at 5€. This is an arbitrary choice, as it will be different for different OEMs and car models. It only shows that depending on this value, so the slope of the line, certain options become more or less attractive.

Most important conclusion is however that there are many opportunities to save both cost and weight at the same time, and even so using various material systems.

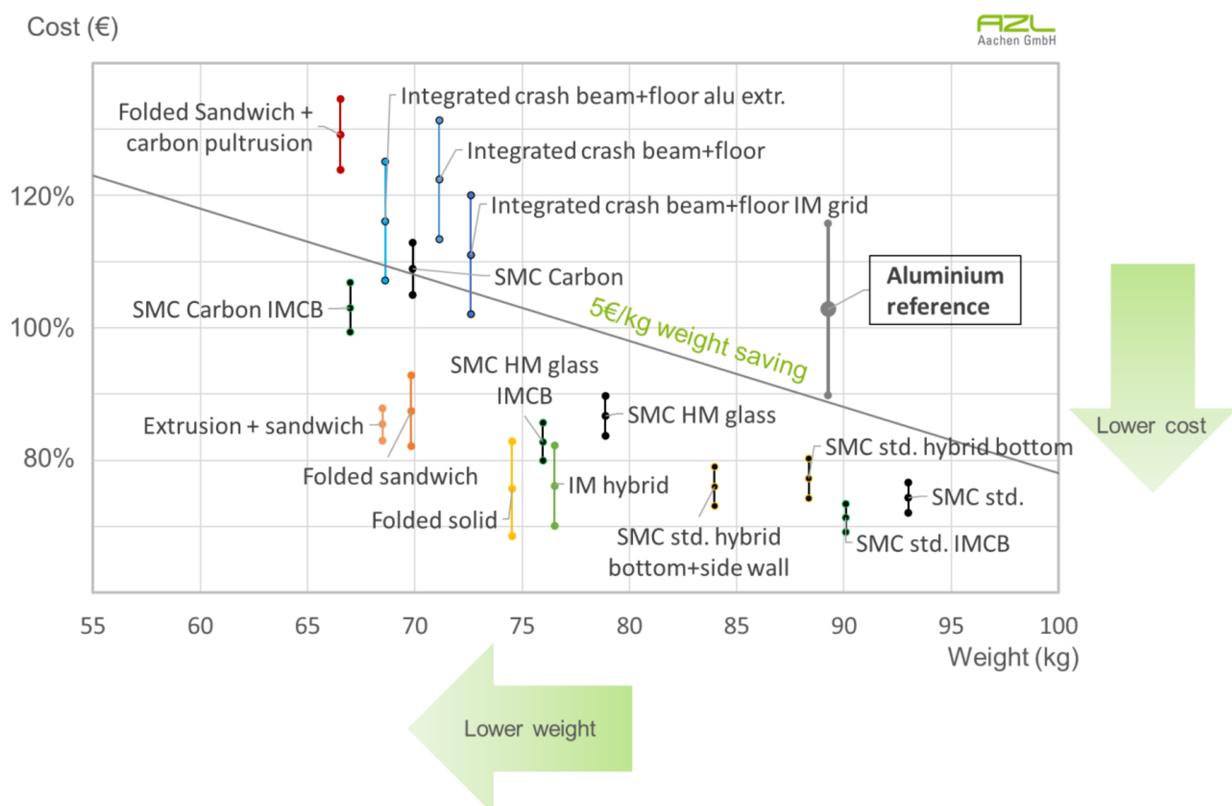

Figure 12: Cost versus weight for different investigated multi-material concepts. 5€/kg weight saving line for visualization only. (IMCB=Injection Molded Cross Beam, HM=High Modulus).

Further considerations

The investigated sandwich constructions typically result in lighter designs. Next, due to the thickness of the sandwich, they'll take more external, or at the same external space yield less internal space at equal mechanical performance. For the same outer dimensions, in this study it yielded typically about 5% less internal space for battery modules. Whether that may be an issue depends on the particular car design, and the magnitude may also vary when considering more detailed requirements regarding thermal insulation, NVH, etc.. An advantage of the sandwich is the better thermal isolation, which may have advantages in battery performance, e.g. by keeping cell temperatures at a more desired level when the car is parked overnight in winter, but also in fire resistance and heat shielding during a thermal runaway event.

All concepts are scalable to different sizes of battery boxes, although at different investment costs. Concepts that use folding techniques, e.g. in case of folding thermoplastic laminates or sandwiches, in fact don't need extra form shape tools for a different size box, while for an injection overmolded concept a different size box will just mean another rather complex mold. Depending on the build rate of the different car variants, this may lead to the choice for the one or other concept. But it should also be noted that at high build numbers, over 100.000 vehicles a year, the tooling cost contribution per casing is only a small part of the total casing cost.

Future developments

Despite the predicted weight and cost advantages for various multi-material concepts, today's battery pack structures are predominantly made from aluminum and/or steel. As a first step OEMs are looking at replacing the less complex components, such as the lid and bottom protection plate, parts that don't affect the battery pack internal design very much. In fact, these are the lower risk parts during the development phase of the complete battery pack. It is expected that experience with composite solutions in lids and protection plates will promote further use for more structural parts in future.

Many electric vehicles on the road today don't comply with the new thermal runaway regulations, requiring 5 minutes escape time after a thermal runaway has been detected, as e.g. stated in ECE R100, or GB38031-2020. For future car models it means that the box structure, and especially the lid, must resist high flame temperatures and particle blast resulting from such a thermal runaway. Depending on cell type, flame temperatures can typically vary between 800 to 1200°C, and unprotected aluminum will burn through in just a matter of seconds. Aluminum can be protected with intumescent coatings, mica layers, or thermal blankets, but also composite materials may have good inherent burn-through resistance, while also protecting the car interior from too high temperatures. Many different solutions are proposed by material suppliers and tiers, but it is difficult to compare them on effectivity and efficiency, the more as everybody tests fire resistance in a different way. For this reason, AZL designed a fire resistance test stand that can test various materials and joints on a material sample level, while collecting strength data under fire loading, see figure 13. In this way the strength results as function of temperature can be used in a CAE analysis to predict whether a complete pack could survive an internal (or external) fire. At present nearly 50 different material solutions are being comparatively tested.

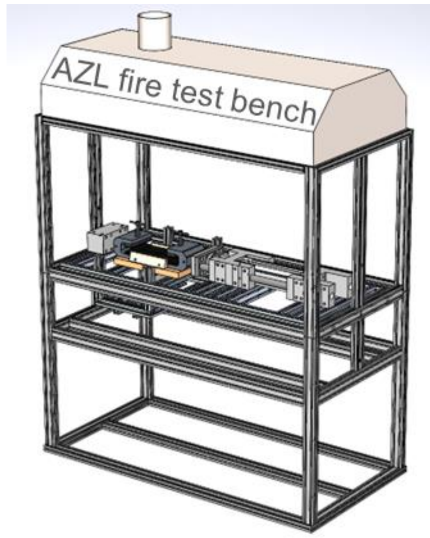

Figure 13: AZL Fire test set-up, for testing materials on strength under fire loading.

Another factor that is important for material choice is the resistance against foreign object penetration to the bottom of the battery pack, e.g. from sharp metal objects laying on the road, and being swept upward as a projectile while driving at high speed over them. This penetration resistance is best characterized experimentally. A test set-up has been made at AZL's partner institute FKA to test impact behavior under oblique angles on material specimens, in a way that is representative for a real underbody protection shield, see figure 14. Different materials can be tested under different impact angles, while also a relation is being found to the more usual ISO 6603-2 or ASTM 3763 perpendicular impact penetration tests performed on much smaller scale specimens. At the same time the damage potential to battery cells during the impact event is evaluated, as composite materials may show little plastic deformation, but still could deform elastically quite a bit during the impact event. The first promising results show that continuous fiber composites can perform well in comparison with currently used aluminum protection shield materials.

It is expected that the layout of battery box structures will develop towards a more efficient cell-to-pack layout, see figure 15, with different levels of structural integration with the car body structure. Challenges for this new layout may be in increased sensitivity for damage, making the previous mentioned experimental material characterizations even more important. Further, different recyclability and repairability options may influence the future designs quite a bit. The new proposed European End of Life Vehicle (ELV) directives are still under discussion [3], and will likely include new rules for plastic materials, while the current directive can already be met with just recycling of metals. Anyway, due to the relative large mass of the battery pack, recycling can't be ignored. How different material and structural layout options could look like and compare on cost and eco-impact will be treated in a next AZL multi-material design study, starting in the second half of 2022.

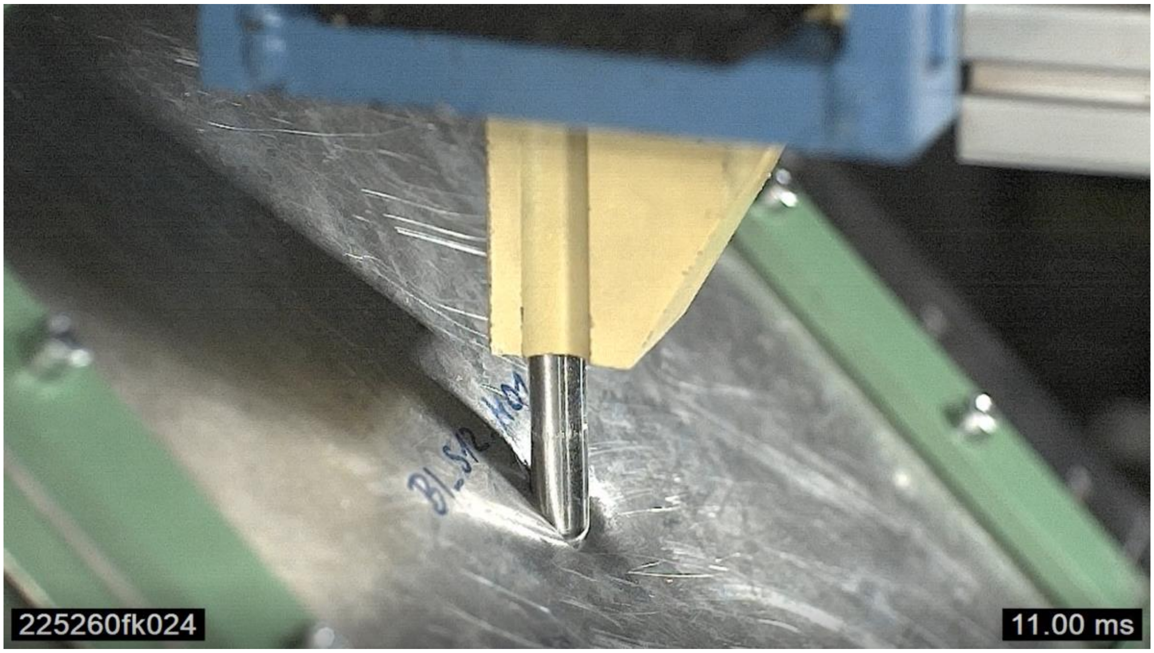

Figure 14: Oblique instrumented impact test set-up, detailed view on impact area.

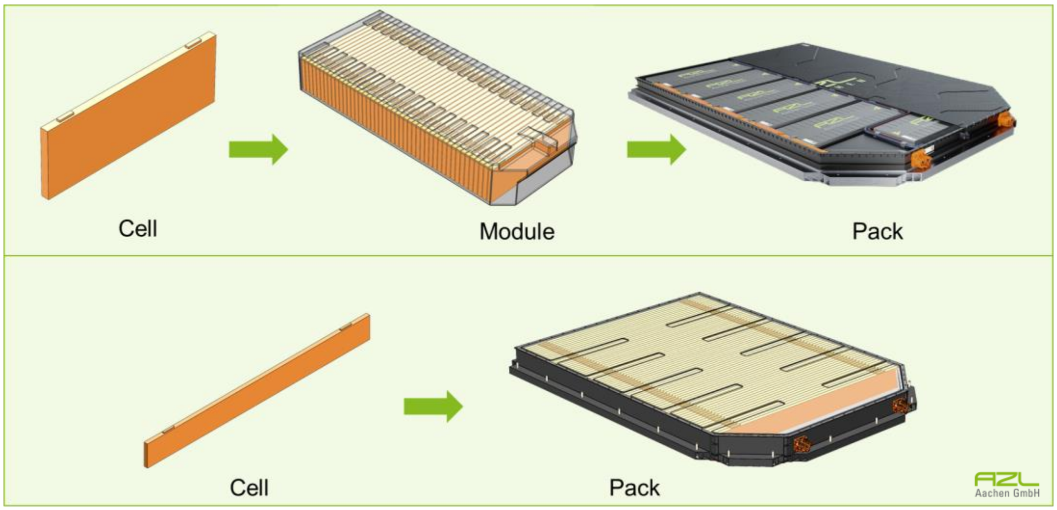

Figure 15: From Cell to Module towards Cell to Pack layout.

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