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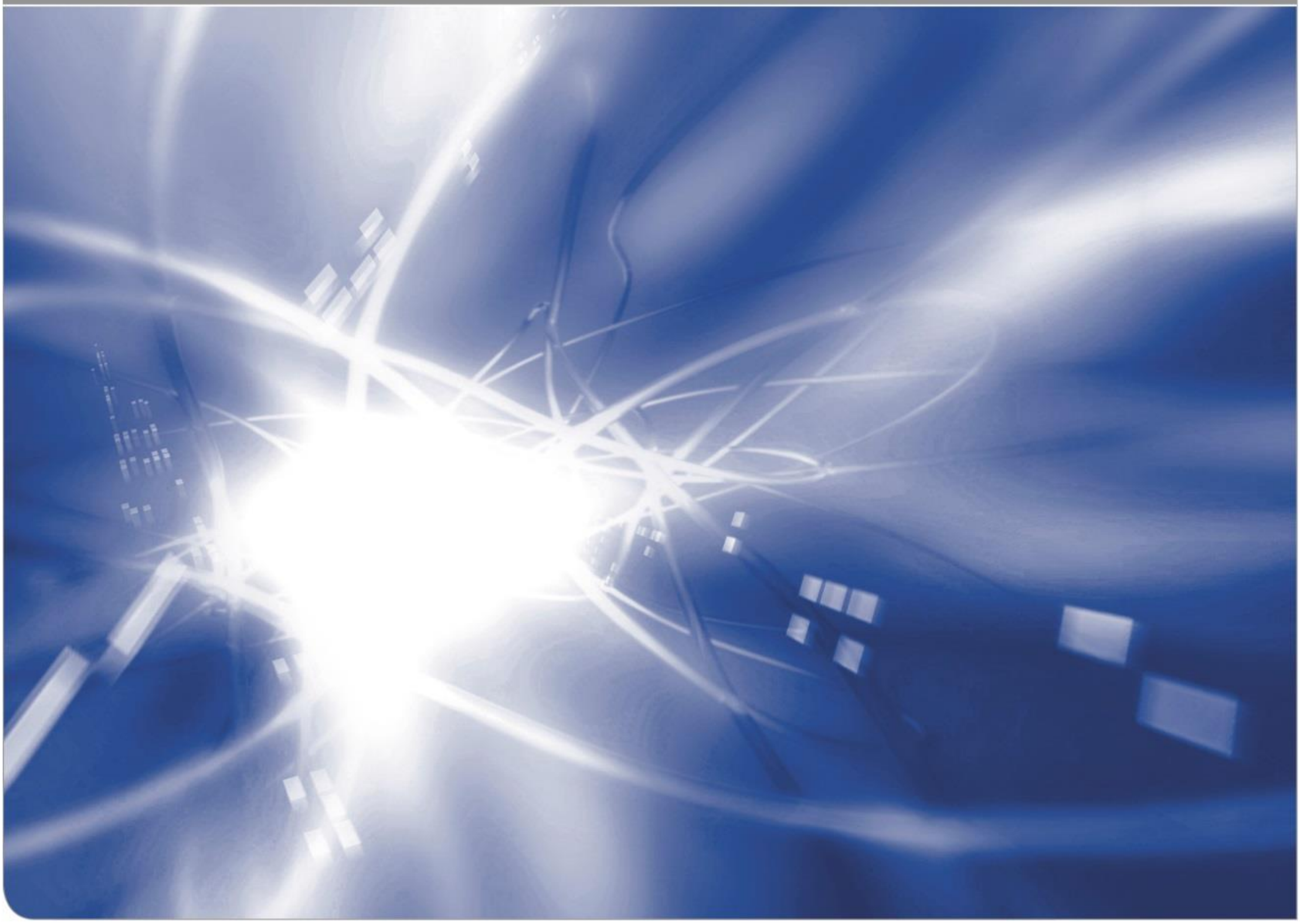

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Abstract.
Due to ever stricter climate targets, the focus across all industries increasingly shifts to the reduction of CO_2 emissions, which, for mobile systems, can be achieved by saving mass through lightweight design. One promising approach to increase the lightweight design potential lies in multi-material design (MMD). This approach uses the material that is best suited to fulfill the function at the respective locations in the system. However, this approach poses the challenge of initially gaining the necessary knowledge of the system in order to select the best material for the job.
This work is dedicated to this challenge as well as the implementation of an MMD for a liquid cooled battery module. For this purpose, the approaches of systemic lightweight design were used, for instance, to identify components with excessive weight and to analyze their lightweight design potential. By coupling CFD, thermal and structural simulations as well as accompanying experiments, it was possible to verify and validate very early during development as well as to incorporate the interactions between product and production directly in the design phase. This made it possible to develop an MMD module design that saves over 60 % of mass compared to the reference system made out of a single material. In addition, it showed that systemic lightweight design and MMD not only reduce mass while guaranteeing the same functionality, but can also decrease costs through smart choices of materials.

Keywords: Multi-Material-Design, Battery, System lightweight design, Extended Target Weighing Approach, CFD, Structural simulation, Thermal simulation, Thermoplastic Elastomer.

1 Introduction

Lithium-ion batteries in battery electric vehicle applications conventionally facilitate a liquid cooling system for temperature control of the battery cells. This is intended to guarantee maximum performance while driving or charging and at the same time to minimize or at least homogenize aging of the battery cells.

With a single-material-design the advantages of a high-performance cell cooling can come at the cost of increased system mass through the use of more heat conducting material, wider fluid channels or more fluid mass flow requiring bigger pumps. This is also evident in the battery module and its patented cell holder [1] from the company Dipl.-Ing. Rainer & Oliver PULS GmbH (see Fig. 1), who initiated this research. The cell holder, which functions to locate the cells but also to serve as a heat conductor is made of aluminum, in which the cooling liquid is guided. While the good heat conducting properties of aluminum paired with high rigidity compared to polymers are desirable in some locations, there are parts of the cell holder, where properties of metal like high electric conductivity might even be disadvantageous.

To lower the mass of the cell holder and to leverage the lightweight potential a combination of metal and polymer is investigated, which uses the right material at the right place. This multi-material-design drastically alters the embodiment of the cell holder by the introduction of different manufacturing processes and materials. To learn about the new material, extensive characterization was performed and to verify the designs the use of supplementing thermal and CFD simulations was facilitated. This contribution also covers the decision process and steps to develop a new product generation and aims to be a guide for future developers on how to identify and proceed with a drastic paradigm shift in design by involving the system perspective and holistic thinking.

2 State of Research

This contribution addresses three fields of ongoing research. To provide the necessary foundation and background, this chapter outlines these three fields briefly.

2.1 Product Generation Engineering

According to Albers et al. [2], PGE - Product Generation Engineering is understood to be the development of a new generation of a technical product by both a specific carryover and the new development of subsystems. It is also intended to facilitate the planning and management of product development projects.

PGE states that every technical product is developed in generations. Thereby the development of a new product generation (G_n) is always based on reference systems as part of one or multiple reference products. Reference products can be internal to the company as predecessor products, or external in the same or even other industries. Interim results from research that have not yet reached market maturity or failed products might also serve as a reference system. [3]

The model is intended to enable researchers and product designers to develop meaningful methods and processes for future product development tasks. Every G_n is exclusively developed through three types of variations. These are the "carryover variation" (CV), the "embodiment variation" (EV) and the "principle variation" (PV). In a CV, no development resources are applied besides minimal interface adjustments if necessary and the subsystem itself is carried over without any changes. With EV, the used principle remains the same, but the embodiment is changed. In PV, for example, a different physical principle is used to perform a task, which usually implies a subsequent EV as well. [4] The model of PGE allows for impact assessment of decisions made within the product specification. Apart from reducing development risk, this also increases the potential for saving resources. [5]

2.2 Lightweight Design

Lightweight design always aims to reduce mass of structures, components and products to the greatest possible extent under given boundary conditions [6]. The target-oriented application of design methods, materials and manufacturing technologies available in lightweight design is one possible way to pursue this goal [7]. In this context, multi-material design (MMD) in particular offers great potential and is increasingly applied [8]. This involves combining different materials at component level in order to exploit the synergies of the individual materials in the best possible way [7].

The available lightweight design strategies are suitable to determine at system level where MMD is useful and to define at component level which materials should be combined. These lightweight design strategies appear in varying numbers and forms in literature [9–12]. In product development, mainly system, form and material lightweight design including a reference system are used. A variety of methods, processes and tools provide the product developer with the necessary support. [13]

In the context of system lightweight design, for example, the Extended Target Weighing Approach (ETWA) describes a useful tool to assign mass to individual functions within a system and then identify areas in the system with high lightweight design potential [14, 15]. Tools such as structural optimization support in form lightweight design. Such optimizations can be used not only in the design phase but also in the concept phase, for example to stimulate creativity. In material lightweight design, the product developer uses materials that have already been engineered, but utilizes them in a specific area of application such as MMD. [13]

2.3 Tuning the Thermal Conductivity of Thermoplastic Elastomers

Thermoplastic elastomers (TPE) are a class of plastics, which combine the mechanical properties of an elastomer and the processing properties of thermoplastics. These two-phase-systems can be obtained in multiple ways. On the one hand, block copolymers can be generated during the polymer synthesis from incompatible hard and soft segments. On the other hand, TPE can be produced by blending through compounding. In this process, the blends are obtained from solid/stiff components and soft/ductile compounding partners [16, 17].

Generally, plastics have very low thermal conductivity (0 to 0.45 W/mK). Semi-crystalline thermoplastics in particular show a temperature dependency in thermal conductivity. Therefore, an increase in thermal conductivity can be observed when semi-crystalline thermoplastics are actively cooled. This is due to the denser packing of polymer chains in semi-crystalline structures and the associated improved heat transport. Another aspect that influences thermal conductivity is the covalent bond density. Better heat conduction occurs at covalent bonds so that elastomers and thermosets exhibit better heat conduction than thermoplastics due to the higher number of covalent bonds [17].

In order to use plastics in the thermal management of components, an increasing research focus is put on the optimization of their thermal conductive properties [16, 18]. One way to increase the thermal conductivity is to add thermally conductive fillers to the polymer matrix. Metallic (e.g. copper), ceramic (e.g. boron nitride) or organic fillers (e.g. graphite) are suitable for this purpose [19]. The thermal conductivity of the compound is thereby defined not only by the molecular properties of the polymer matrix described above, but also by the conductivity, orientation, geometry, interaction and the proportion of fillers [20, 21]. However, a higher filler content also changes other material properties such as viscosity, elongation at break and strength [20].

With regard to the TPE described above, achieving the highest possible thermal conductivity while retaining the preferred mechanical properties of elastomers is still a challenge. Other filler requirements, such as electric insulation, limit the choice of available fillers. The development of thermally conductive elastomers is already further advanced. However, elastomers cannot be recycled. This is where TPE offer a major advantage. Therefore, the compounding of thermally conductive TPE is still an ongoing research topic. Consequently, only a few TPE grades suitable for battery thermal management are available on the market. In addition, only limited information (e.g. on processability) is available on the commercially available grades.

3 Objectives

The aim of this contribution is to investigate the process of developing a new product generation G_n facilitating multi-material lightweight design and lay out the individual steps and decisions.

The primary reference system is depicted in Fig. 1 and consists of a type 18650 cylindrical cell holder conventionally manufactured out of aluminum. Cut outs are milled into the cell holder for insertion of the battery cells previously wrapped in a heat conducting, but electrically insulating silicon tube before insertion. This silicon tube not only contributes 7.6 % to the total module mass including the battery cells themselves, but also poses environmental concerns because of poor recycling capabilities and is also a cost driver. The aluminum cell holder (reference system) itself accounts for 15.2 % of the total module mass of the reference product including battery cells and is therefore the single most heavy component of the battery module (reference product). These mass concerns shall be remedied by G_n.

New requirements for the cell holder include an easy disassembly process for recycling, general recyclability of all materials and a modular approach. This modularization is twofold. On one hand within the cell holder assembly to subdivide the cell holder into small and easily manufacturable subsystems with high individual piece counts, but also for the cell holder assembly itself in order to create differently sized battery modules and allow for non-wasteful repairs. As the new designs features a different and uncommon polymer material, supplemental testing and characterization of this material was carried out and the processability was investigated in order to provide data for the design and future product developers.

As Nöller et al. [15] already stated, changes to a component within the investigated battery system require a methodical and holistic approach from a system perspective, as the components are interdependent and might cause unforeseen or even unwanted consequences. Therefore, the interfaces with the cooling system and the battery cells is of great importance and need to be assessed thoroughly.

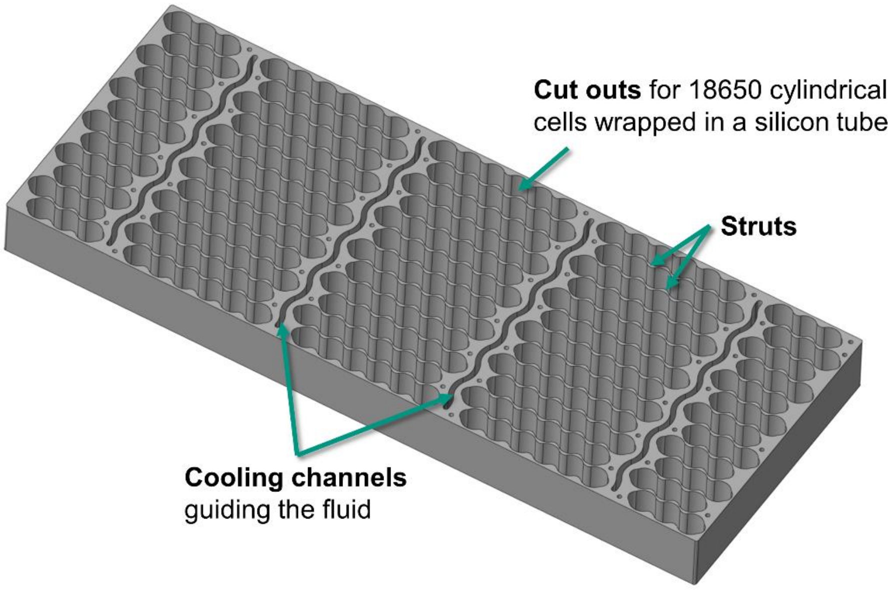

Fig. 1. Reference System: patented single-material cell holder made out of aluminum, model based on [1]

4 Method and Results

This chapter is comprised of the main research work for this contribution. It starts by briefly discussing the previous work performed by the authors to lay a foundation for the taken steps and decisions. It proceeds to highlight the analysis and concept synthesis, the testing of the new material and concludes with the newly implemented design supplemented by verifying simulations.

4.1 System Analysis and Functional Lightweight Design

As laid out in previous research by Nöller et al. [15], the cell holder was identified very early in product development as the component with the biggest lightweight potential within the battery module and first steps were taken to reduce its mass by lowering the height of the cell holder by more than 50 % through EV. Subsequently, an engineering generation (EG, these represent intermediate stages in the development [22]) of the cell holder was created. The insight to choose this component was gained by performing a methodical reference product analysis guided by the Extended Target Weighing Approach (ETWA) [14, 15]. The result is shown in Fig. 2. In a later study [23], the remaining cooling system components were also overhauled and a methodology was created to efficiently simulate and design a cooling system with parallel flow by using 1D and 3D CFD simulations.

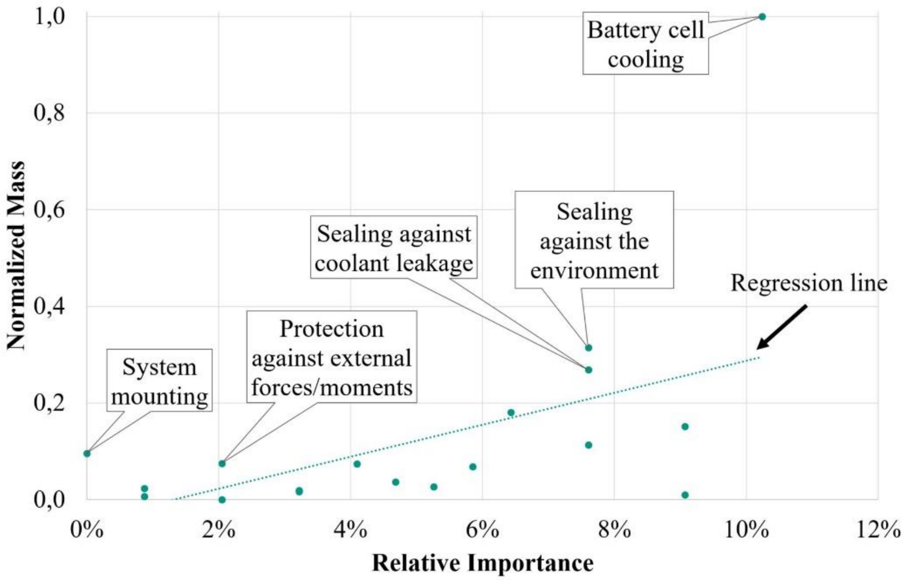

Fig. 2. Reference product analysis result highlighting the Battery cell cooling as the heaviest function of the product [15]

Nevertheless, larger changes to the core structure of the cell holder were not performed and the single-material approach was kept. Extending on this groundwork, the cell holder still holds potential for further mass reduction, function integration and better assembly, disassembly, reparability and sustainability, which is discussed in the following.

4.2 Morphological Box and Concept Selection

The first step for the development of the MMD cell holder is the creation of a reference system in terms of PGE – Product Generation Engineering. The current generation of the battery module served as the reference product in this case with the cell holder shown in Fig. 1 comprising the primary reference system to be brought into the next generation. Using this reference system as well as system, form and material lightweight design, including the methods, processes and tools applicable therein, a variety of concepts for a light, modular cell holder were generated. These are supposed to have an MMD and thus offer great flexibility for the configuration of the different materials consisting of metal and polymer. Due to the resulting strongly varying mechanical as well as thermal material properties, in addition to classic creativity methods (e.g. 635 method), initial structural optimizations are used. The latter allow different perspectives on the problem as well as design proposals to be obtained. In addition, the material properties can be considered during concept development. Furthermore, computer-aided concept development can be used to integrate individual parameters such as material properties or dimensions, to derive their effects on the overall system as well as to draw conclusions.
Subsequently, the concepts are clustered and evaluated on the basis of evaluation criteria derived from the requirements like assembly or reparability. Finally, the most promising approaches of one or more concepts were extracted and inserted into a Morphological Box in order to build a final concept.

In the context of this contribution, eleven different concepts for the G_n of the cell holder were generated. Analyzing these concepts for commonalities as well as differences and clustering them allowed to derive a Morphological Box with six problems, each with several partial solutions (see Fig. 3). Those were then evaluated based on the following evaluation criteria: Manufacturing and joining processes, lightweight potential, thermal management of the cells and ease of assembly, disassembly, reparability as well as sustainability. Looking at the six identified problems, they can be combined into three problem groups solving challenges stemming from the paradigm shift from single to multi-material-design: Preloading, Joining and Tolerances. These groups are not independent from one another, as one partial solution might have effects on the other problems and their respective solutions. Therefore, looking at them from a system perspective is important.

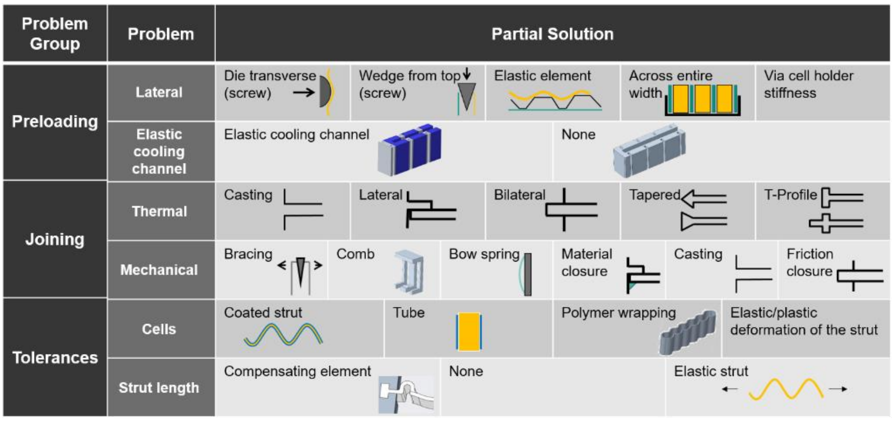

Fig. 3. Morphological Box for the selection of a light, modular cell holder concept.

Preloading. This refers to the fixation of the cells in order to avoid unwanted relative movements between the cells and the struts. The possibilities offered by lateral preloading and preloading by the means of an elastic cooling channel were investigated. The latter was discarded due to uncertainties regarding the sealing and manufacturing. Lateral preloading at individual points, including the necessary external support on the housing, also had to be discarded due to the increased assembly costs and the need to redesign the housing. Therefore, the choice fell on lateral preloading across the entire width of the cell holder. This is an EV compared to the previous lateral preloading by insertion of tube wrapped cells into tight fitting cut outs of the rigid aluminum cell holder.

Joining. The term "Joining" refers to the connection between the strut and the cooling channel, which is necessary for a modular design of the cell holder. In addition, the mechanical load capacity and thermal conductivity are significantly influenced by the choice of connection. For these connections, both frictional and material connections were analyzed. For this purpose, in addition to literature research and discussions with experts, preliminary tests and simulations were used to estimate the behavior in use. From this analysis, frictional connections were deemed uneconomical due to the large number of preliminary tests required with regard to parameter settings and permanent sealing and were therefore discarded. On the other hand, material connections are less problematic in terms of sealing due to the extensive knowledge of manufactures. In addition, they can be superior to frictional connection in terms of thermal conductivity. This is an example of PV by changing the principle of how the system is created and how the heat is transferred in comparison to a conventionally fabricated aluminum cell holder made from stock.

Tolerances. The last problem group describes the necessity of an additional elastic element or a design implementation to compensate for tolerances of the cell diameters at the interface “strut – battery cell” and for tolerances of the strut lengths at the interface “strut – cooling channel”. This problem group accounts for the holistic system view and the newly created or changed interfaces. Due to increased manufacturing costs and a reduction in the lightweight potential, only a coating of the struts was considered for the tolerance compensation of the cells. For the same reason, elastic struts, meaning thin but therefore higher struts, were used for tolerance compensation of the strut length. To meet the requirements for this coating, finding a lightweight material with good thermal conductivity and electrical isolation was necessary. At the interface to the battery cells this comprises an EV, since elastic material was used in the reference system as well. For the interface between the struts and the cooling channels, a PV was used, since this interface is newly created.

4.3 Material Selection and Characterization

One focus of the new battery cell holder concept was to substitute the necessary silicone tubes used as gap fillers for inserting the battery cells. At the same time, the functionality of the thermally conductive and electrically insulating properties as well as the elastic behavior had to be retained. Additionally, to make sustainable use of plastics resources, only thermoplastics should be selected as the substitute material because of their recyclability. Therefore, thermally conductive TPE were considered during the development of the cell holder. However, only little information on the processing possibilities and on the exact material properties of these TPE types is available, especially with regard to a subsequent application in a battery system. For a better assessment, therefore, a representative thermally conductive TPE was comprehensively characterized using various plastic technology methods. For this purpose, the commercially available TPE grade CoolPoly D8102 from Celanese (Dallas, USA) was selected. This plastic type contains thermally conductive and electrically insulating fillers.

First, the processability was investigated by injection molding using an Allrounder 370S 700-100/70 multicomponent injection molding machine from Arburg, Lossburg, Germany. In order to achieve the desired weight reduction, a mold with variably adjustable thickness (0.5 to 10 mm) was used to investigate the minimum component thickness that can be realized from the TPE. At a thickness < 1 mm, the melt congealed directly on the mold wall due to the high thermal conductivity and prevented further melt from flowing out of the die. This ultimately led to a mold cavity that was not completely filled. At various positions of the injection molded test specimens (with 1.5 mm thickness), the thermal conductivity was subsequently determined using the laser flash method (device LFA 447 Nano-Flash Netzsch, Selb). Figure 4 demonstrates the injection molded geometry with the measuring position. Table 1 summarizes the measured values for the thermal conductivity at 23 °C and 80 °C.

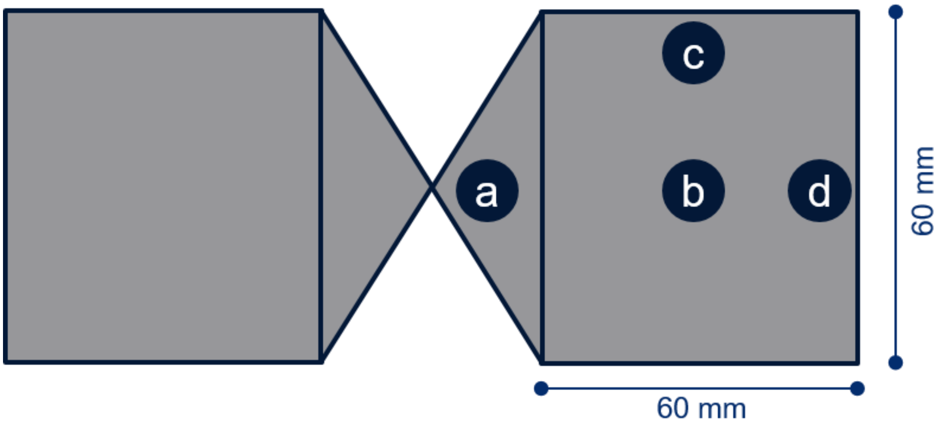

Fig. 4. Presentation of the injection molded geometry as well as the position for the measurement of thermal characteristic values.

Table 1. Thermal conductivity measurement results for TPE.

Position	λ at 23 °C in W/mK	λ at 80 °C in W/mK
a	0.74	0.78
b	0.78	0.84
c	0.89	0.96
d	1.08	1.14

Depending on the measuring position and temperature, thermal conductivities between 0.74 and 1.14 W/mK were obtained. The position-dependent thermal conductivity can be attributed to the non-spherical filler geometry and its alignment during processing. This anisotropy of the thermal conductivity plays a major role in the component design. However, the values for the thermal conductivity are significantly higher than those of unfilled plastics. Furthermore, they are similar to the conductivities of a silicone tube previously used for the cell holder. Further investigations showed that the mechanical properties of the TPE are comparable to those of the silicone. At room temperature, a hardness of 46 Shore A was measured for the TPE.

For a further evaluation of the processability, the TPE was analyzed in the extrusion processes using a single screw extruder 300P from Dr. Collin (Germany). It was found that TPE is also suitable for extrusion into flat sheets with a minimum thickness of 0.3 mm. The variability of TPE with respect to the possible processing methods can be attributed to an appropriate filler content. So, the thermally conductive TPE is a promising material for an application in battery thermal management. Additionally, it is also recyclable and can be processed into a wide range of components.

4.4 Design of the new product generation G_n

The knowledge gained from the reference product analysis as well as concept selection and material characterization lead to the cell holder being designed as follows: The preloading is applied laterally across the entire width of the cell holder, a material connection is used for the joining between the strut and the cooling channel, and the tolerances are compensated by the TPE in conjunction with elastic struts. In order to design such a cell holder considering the boundary conditions, an iterative design alternating between embodiment design and simulation phases is used. The latter consisted of both FEM simulations as well as coupled thermal and CFD simulations. The FEM simulations modeled the interaction between the cells, TPE and struts and were used to determine the preloading required to secure the cells, taking into account the resulting friction pairing between TPE and the cells. Furthermore, it was possible to determine whether the preloading in combination with the thickness of the struts was sufficient to compensate for the tolerances. The coupled thermal and CFD simulations used a model comprised of the cooling channel including cooling medium as well as the struts, TPE and the cells. The cells were subjected to a heat generation modelling actual operating conditions, which resulted in a temperature distribution due to heat conduction via the struts into the cooling medium. This coupled simulation made it possible to vary the connection between the struts and the cooling channel in such a way that the temperature distribution across all cells is as homogeneous as possible.

The design went through six distinct engineering generations EG as depicted in Fig. 5, with the first one representing an initial mockup of the newly modularized cell holder and also served as discussion basis for the production and assembly processes. The subsequent EG Two and Three refined the cell holder and focused on a working concept for a cooling system and preloading respectively. EG Four and Five then improved on these basic concepts as more knowledge about the TPE was gained and first results from the supplementary simulations were achieved. Additionally, the cell holder interfaces with the system were investigated and changes made accordingly. EG Six then saw a last drastic change to the cooling system in order to save more design space by implementing flat cooling ducts and also moving both ducts to one side of the cell holder, both being EV. The fluid is now changing direction by 180° within the cooling channel, an EV only made possible by cutting the cooling channels open in the new design. This change again was accompanied by a coupled thermal and CFD simulation to ensure function fulfillment. With the latest results from FEM simulations the preloading was also centralized and simplified. The found solutions for the three problem groups identified in chapter 4.2 are discussed below in more detail. The final EG solves all problem groups and saves a total of 60% of system mass compared to the reference system.

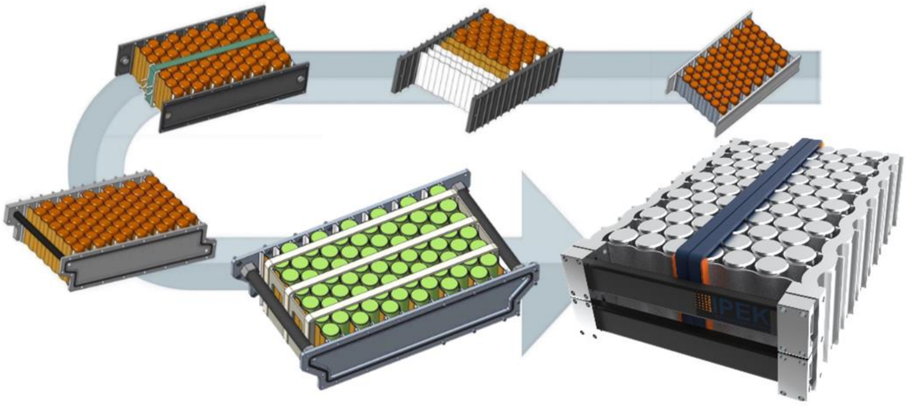

Fig. 5. Engineering generations of the cell holder, from early concepts to a final product

Preloading. As discussed in section 4.2, the choice fell on lateral preloading over the entire width of the cell holder. The solution can be seen in Fig. 6 bottom right. The required minimum preloading force during operating conditions needed to be applied on both sides to the outermost struts. The forces as well as the point of attack were calculated with a linear elastic FEM simulation including the friction between the

TPE and the cells. Considering preload force losses due to setting and thermally induced loss of Young's modulus in the TPE, a preloading solution was necessary, which had elastic capabilities as a static force would be greatly diminished, if the inner geometry shrinks due to setting or thermally induced parameter changes.

The idea to separate the functions into an elastic component and a force providing component was discarded, as the only viable elastic candidate was the TPE and the elastic capabilities were not sufficient for shrinkage compensation. Therefore, the elasticity should be provided by the preloading component itself. As a solution was preferred which wraps around the cell holder assembly, an elastic band was chosen. Carefully dimensioned, all shrinking effects can be considered and the right unloaded length can be chosen. To distribute the forces evenly into the strut, a polymer piece was designed and optimized. As the polymer piece follows the curvature of the strut, the bands are slightly shifted to one another.

Joining. For a material connection, laser welding was the most probable candidate, as the heat generation is very local and the process can be automated. In addition, a welded connection provides good heat conduction as well as a rigid connection between the struts and the cooling channels. The selection of the metal used for the cell holder is strongly influenced by the choice of the manufacturing processes involved. To ensure a rigid connection, different FEM simulations with worst-case loading on the joints were performed ensuring safe operation at all times. Fig. 6 upper right highlights the weld area.

Tolerances. Nöller et al. determined the necessary aluminum cross section for sufficient heat conduction [15], but due to the limitations of a single-material-approach was confined to a set strut thickness resulting in a decreased cell holder height. As the new G_n does not have this limitation anymore, thinner, but higher struts with the same cross sections could be used. This resulted in a multitude of benefits for the overall design. The dimensions of the overall product could be reduced substantially, because the full height of the cells could be used to transfer the heat and the thinner struts meant a thinner overall width. Additionally, the second area moment of inertia of the struts resisting the cell insertion was much lower, resulting in a considerably easier assembly process. This is further amplified by providing the preload from an external band and not the cell holder's internal rigidity, further improving on assembly. These benefits also resulted in decreasing the necessary thickness of the coating by 50 % in comparison to the reference product's silicon tubes, lowering dimensions and saving mass (Fig. 6 bottom left). The strut length tolerances were considered by the welding process itself. Instead of welding the struts straight onto the cooling channels, the struts were welded on small protrusions, allowing for tolerance compensation. During the welding process, the two cooling channel sides are firmly held in place, while the struts are positioned in between and are themselves dimensioned allowing only for a negative tolerance on overall length.

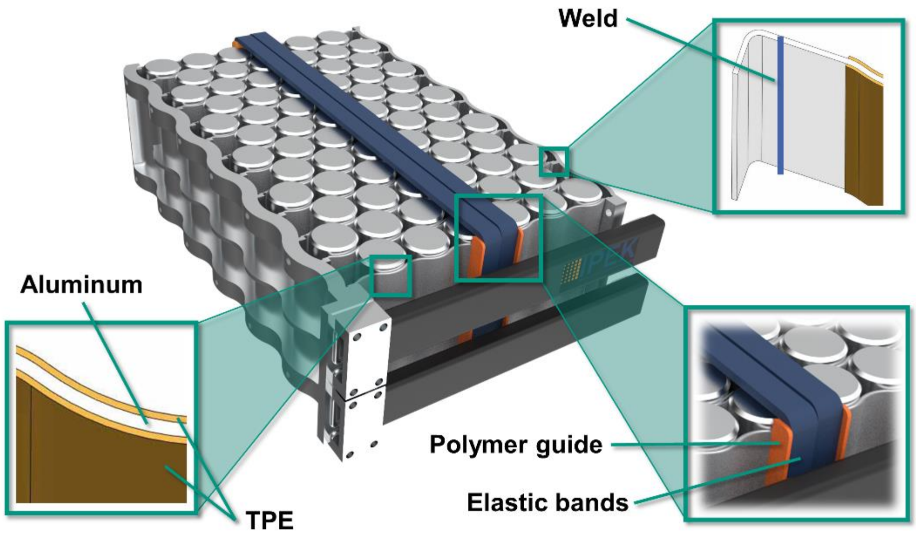

Fig. 6. G_n: Solutions to the three problem groups

5 Summary and Outlook

This contribution elaborates on the process of developing a new product generation with a drastic paradigm shift from a previously single-material-approach to a multi-material-approach. It facilitates the model of PGE – Product Generation Engineering and derives new solutions methodically and from a holistic system perspective including the interfaces of the system in development.

Starting from a full system analysis with the ETWA, it is determined, that the cell holder holds great potential in terms of lightweight design. Through the generation of concept ideas, clustering and evaluation against requirements set on a system level new solutions and core problem groups were found. The novel and uncommon TPE material was characterized and the obtained data subsequently used in the design and simulation process. Lastly the function groups were partially solved and combined into one solution as the new product generation G_n.

Compared to the reference system, the new generation saves more than 60 % of mass, while providing new functionality, an easier assembly, disassembly and repair process and makes use of more recyclable materials. Furthermore, the dimensions are greatly reduced, resulting in the possibility to fit the whole cooling system previously external to the cell holder within the envelope of the previous solution, which leads to a greater module energy and power density.

This research understands the design of the embodiment not as the execution of previously made decisions, but rather an interdependent part of product development. The necessity to consider the whole system, to iterate on the embodiment during development and not after, to verify assumptions and check for unnoticed effects on system level with simulations and to take production, assembly, repair and environmental concerns into the initial set of requirements to formulate the objectives to be achieved by this development is strongly emphasized by this work.

In the future, the modularity and integration of the new Generation G_n into vehicles is investigated in more detail. A consecutive research project currently investigates the integration of battery submodules by insertion or substitution of structural parts of vehicles as a means to utilize already existing housings or structural parts and their rigidity for housing of the battery cells or to contribute to the overall structural integrity with the battery cells or battery housing directly. This further structural integration of the battery system into vehicles shows great potential for even more lightweight solutions by avoiding redundant structures.

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