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Opportunities of Metal Structures in Cooling Systems

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Abstract. The growing market of power electronics in the mobility sector leads to an increasing demand for cooling systems. In the project this need to improve performance is to be met by adapting the cooling structure. Depending on the intended application of cooling systems - automotive, railway and aerospace - different requirements are defined for the cooling process resulting in varying conditions for the design. So metallic foam structures are under investigation because of their high inner surface. Two different process lines are most suitable for the aimed application. The production and optimization of galvanized foams seems to be the most lucrative for a low-cost product, while 3D printing is currently only worthwhile for special applications such as aerospace. As a potentially more cost-effective process, which is already being used for small series, investment casting structures are being investigated as an alternative. Depending on the production process chosen, corresponding requirements for structure creation suitable for production apply. Corresponding process adaptations are also taken into consideration. The first optimization step is an analysis of the conventional open cellular metal foam structures using CT. The results of the CT evaluation, together with the empirical data for fluid mechanical and thermal characteristics, are the basis for a later replacement model of the CFD simulation. Besides the Kelvin cell, which is a good geometrical substitute for the conventional structures that copy the Polyurethan master pattern, other cell types are also considered. Alternatively, structures based on mathematical cells e.g. Schwarz P/D, offer the possibility of separating two media to create cross-flow or counter-flow heat exchangers. Regardless of the chosen system, the main task of the investigation is to find an optimum of the relation between pressure drop and heat transfer performance for the corresponding system and to design the cell arrangement in a way that is suitable for manufacturing. This justifies, among other things, the investigation of a minimal surface structure, which at first seems contradictory. Considering the manufacturing process to be defined beforehand, requirements such as self-supporting design (additive process) and free accessibility (electroplating) also play an important role in the structure development. Thus, the goal is still to optimize the cell and web geometry accordingly.

Introduction

For the improvement of commercial cooling systems for power electronics the application of cellular structures seems to be promising in order to enlarge the surface for heat transfer. As already investigated in several publications the use of metal foams can improve the thermal distribution for cooling[1]. To obtain reliable results, the use of cellular structures designed, adapted and evaluated for three well-defined use cases is objective of a current research project. In the KoLibri project, funded by the BMWK, the cooling performance for high-performance

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electronics in the mobility sector is being investigated. Three use cases were distinguished: the automotive sector, railway industry and the aerospace sector. All of those topics show partly conflicting requirements for the design of (new) cooling systems. In order to be able to meet the corresponding requirement profiles, simulation plays an important role in the design in addition to construction. Furthermore, the differing requirements lead to different manufacturing processes, such as the galvanic or investment casting.
Finally, the eco-balance has to be kept in mind. A not less important goal of the structural design is the consideration of the ecological impact already in the first engineering steps.

Cooling of high-performance electronics in the mobility sector
The division of the mobility sector into three main industries is necessary for a sensible design of a cooling solution, not least because of the different unit numbers, prices and requirements.

Whereas in the aerospace industry, price tends to take second place to safety and weight savings, in the automotive industry it is the driving factor.

For the automotive industry, for example, it is also necessary to consider an alternative manufacturing route, since investment casting, which is sufficient for the low volumes in the aerospace sector, is rather not an option.

One possibility to withstand the cost pressure would be the electroplating process suitable for large series production. This also seems to be a good alternative due to the material component copper. However, new challenges also arise here. For example, wettability and permeability for the electrolyte into the structural design of cells. At this point, simulation is of elementary importance for any product design. In order to create a holistic picture, the thermal-electrical simulation is carried out first.

An essential and permanent part of the simulation setup is the validation based on measurement results. For this purpose, the demonstrator underwent an evolution (Figure 1). It was further developed from a highly geometrically reduced model to a test setup adapted to the PinFin cooler to the final benchmark the commercial PinFin solution.

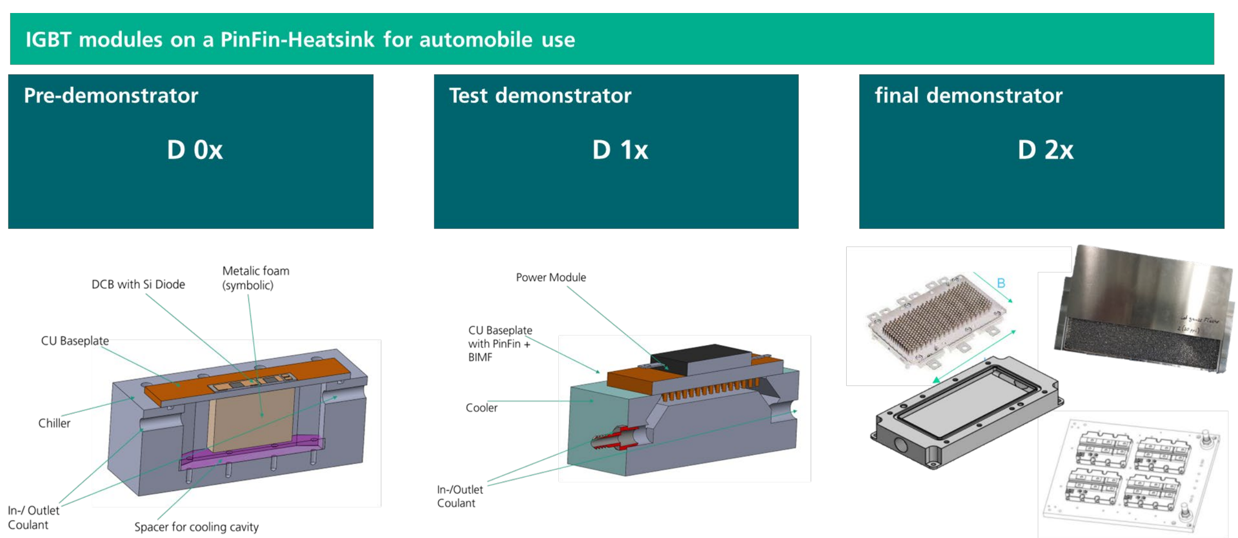

Figure 1 Evolution of the Test demonstrator

In addition to the pure validation, these demonstrators should also support the coupling of the different simulation modules (electro-thermal + fluid dynamic).

As a final step, a link with the LCA software “UMBERTO” is intended to enable optimization at this level as well and to include it at the earliest possible stage.

Evaluation of the thermal behavior of power modules using numerical simulation

Together with the partner ILK, Fraunhofer ENAS developed a methodology for the simulation of the thermal conduction behavior of the overall assembly. This work aims at combining the two fundamentally different simulation applications “electro-thermal evaluation of power electronics” and “fluid dynamic evaluation of cooling”. Since the results of both simulations influence each other (a better cooling causes a change of the power dissipation of the power module and vice versa), the coupling of both simulation types via a common interface is necessary and shown on the realized demonstrator in Figure 2.

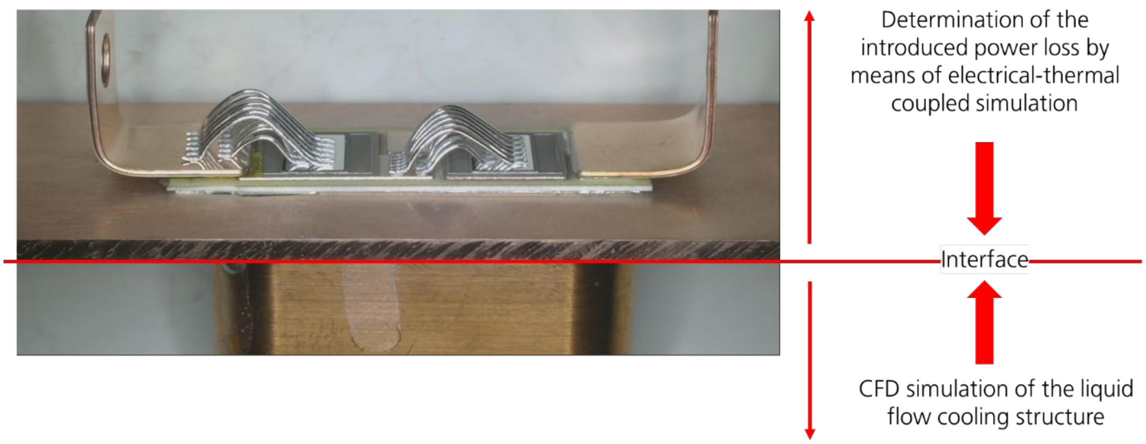

Figure 2 Assembly used to validate the combination of electro-thermal and the CFD simulation

The focus of the work of Fraunhofer ENAS is the development of an electro-thermal simulation model. **In a first step**, this model is calibrated based upon the concept demonstrators, which are manufactured and experimentally evaluated by the partner Siemens. For this purpose, all input parameters necessary for a trustworthy simulation, such as correct geometry and material data, were determined and the model was built. In several iterations, the model was calibrated using experimentally determined data from the partner Siemens (Figure 3).

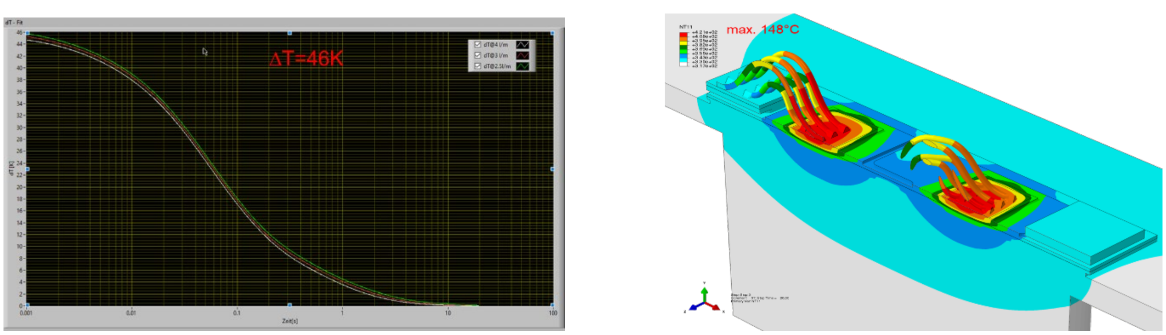

Figure 3 Calibration of the junction temperature of the dies by means of electro-thermal coupled simulation

Furthermore, for the fluid dynamic simulations of the partner ILK, the expected heat transfer conditions are transferred at the “simulation” interface (Figure 4), so that the electro-thermal simulation can serve as boundary condition for the CFD simulation.

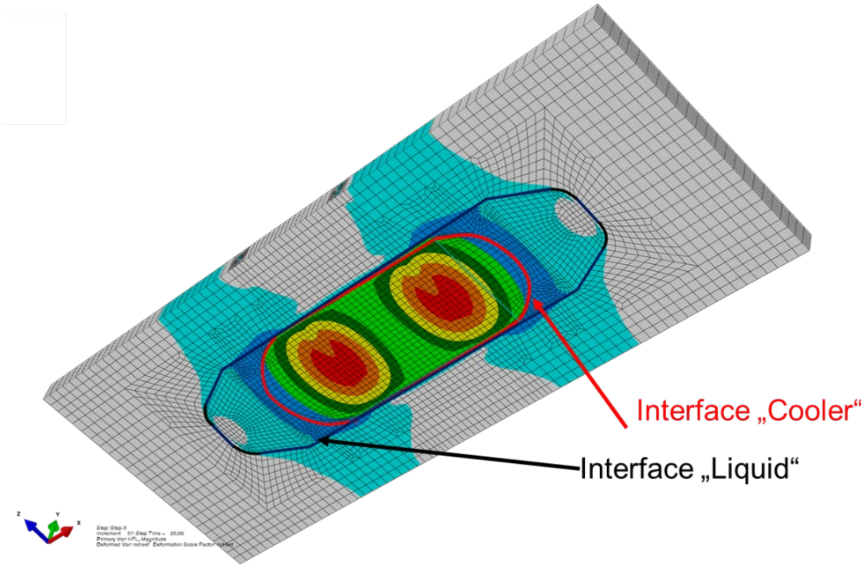

Figure 4 Averaged Heat Flows at the “simulation” interface

For this, however, it is necessary to drastically reduce the effort for the electro-thermal simulation. Therefore, **in the second step**, this model is converted into a simplified behavior model – a so called “surrogate model”. By means of a DoE, the surrogate model leads to a response surface (Figure 5).

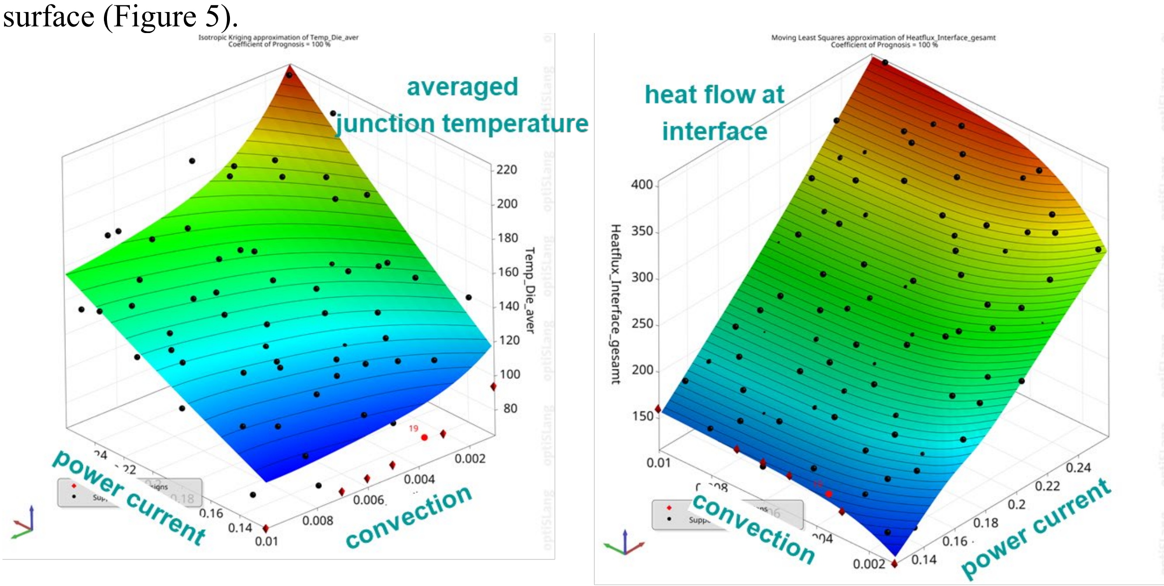

Figure 5 Surrogate Modell (Response Surface Method)

With the help of the surrogate model, results were predicted and further on successfully verified by experimental measurements. The surrogate model is therefore trustworthy.

The next steps include the conversion of the surrogate model into a recognized exchange format. That way it can be used in other simulations as well as integrated into system simulation programs. Furthermore, it is planned to extend the surrogate model in multiple directions such as the consideration of ecological aspects in model design. Another use would be the integration of the thermomechanical reliability of the assembly and connection technology used, represent a major challenge.

Some of the simulations shown above are related to solutions that are partly state of the art as the design of the coolant flow wasn’t changed much. To step ahead it was mentioned already that one approach is to optimize the heat distribution and influence the flow of the cooling liquid by application of cellular metal structures.

Optimizing cellular metal structures to create maximum cooling efficiency

Based on the results of the electro-thermal simulation, the structural optimization can also be started. After a detailed examination of the structure of stochastic foams by means of CT, the influence of the cell structure needs to be evaluated on the basis of different CAD-modelled cells. Thus, the mathematical description is done already in several publications e.g. based upon Kelvin cells.[2]

One intention using those substitute cell models is the optimization adapted to the thermal load case. By using a combination of topology optimization and the Software SYNERA a homogenous cell structure can be changed in strut thickness to the thermal load case represented by a thermographic picture. That way the flow resistance and heat transition can be optimized for any location within the network leading to the best possible cell structure.

Parameter determination for the structure optimization

Some technologies such as galvanic coating and investment casting have been mentioned already. All design and LCA development processes are based upon parameters of the production. In order to get precise figures for those simulation and computer aided optimization it is necessary to produce several samples for testing. The two mentioned processes are taken into account, the galvanic process, as copper foams are already commercially available (6) and the investment casting process shown in 7.

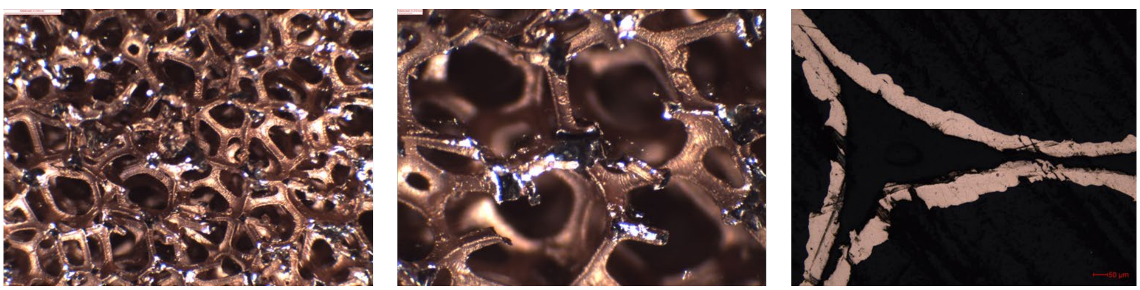

Figure 6 Commercially available copper foam

The CAD-structures (a) are 3d-printed in wax (b), which is cheaper than a commercial metal-print and has a resolution down to 16 µm. Afterwards the investment casting process starts with the embedding of that master pattern in molding material (c) a dewaxing and heat treatment of the mold, followed by infiltration of the emerged cavity with molten metal. Once solidified the structure can be unmolded by destroying the "invested" mold (d) and is finally cleaned by high pressure water jet. Finally, a post machining such as cutting the gating and feeding system is resulting in the wanted metal structure (e).

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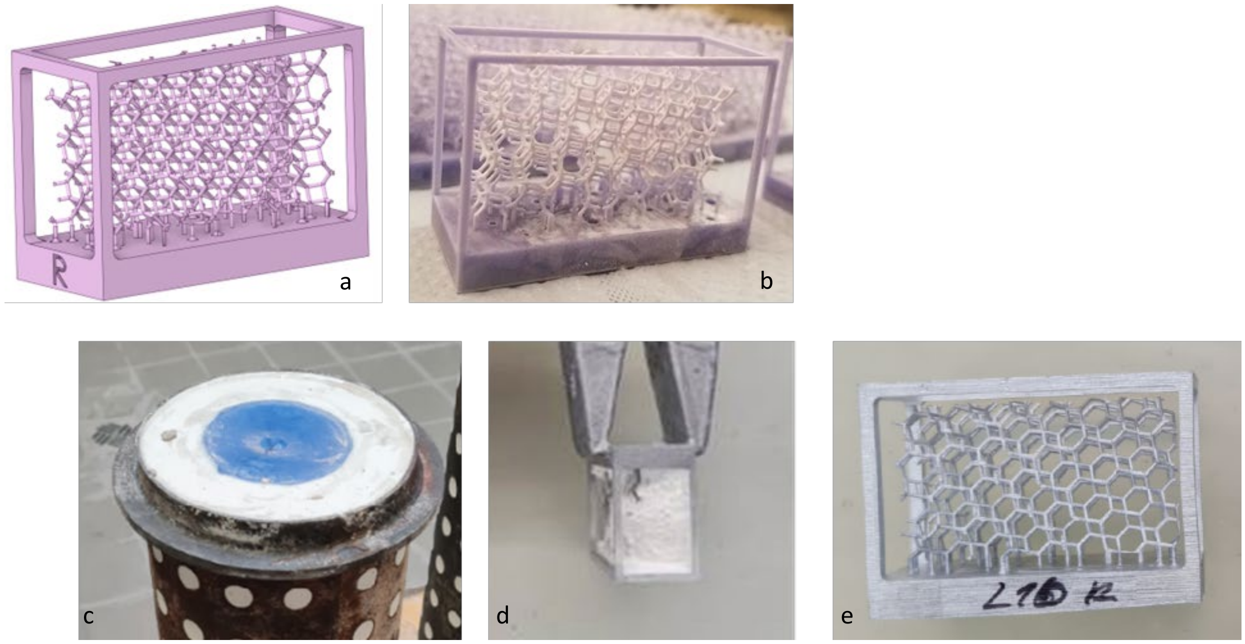

Figure 7 Investment casting process for an open cellular metal structure

Reporting the whole process and parameter determination lead to the next important step of the project.

Life Cycle Assessment (LCA) and recycling of metal foam-based cooling structures
The importance of an LCA for all processes is shown in 8 illustrating the tremendous environmental impact of a product in the "end-of-life" phase.

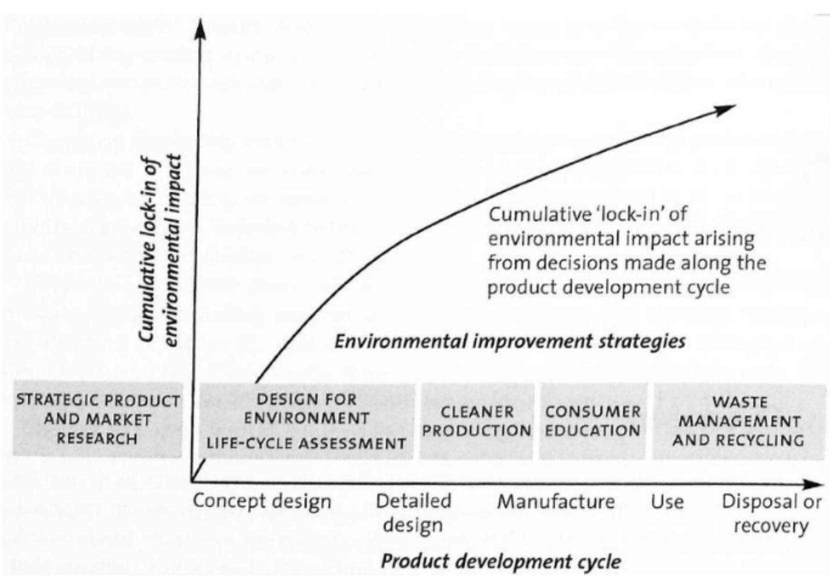

Figure 8 Investment casting process for an open cellular metal structure [5]

For every product in today's, a life cycle analysis and a suitable recycling concept are already in the foreground in the development phase, in order to create a sustainable and holistically considered product and processes right from the start. In this context, LCA is used, among other things, to integrate sustainability aspects during development or to create process routes, including these processes that are downstream from the actual life cycle, such as recycling [3][4].

In order to be able to compile these in detail, well-founded data must be available. When a new process or product is developed, this data is usually not available and data gaps occur which have to be closed by tests and assumptions until final data is determind. In order to provide a first overview, a screening LCA is usually set up, which is not ISO compliant, but provides a first reference point to select suitable processes in the course of a new development [6]. In this context, the LCA of the recycling route is particularly important, as it has a direct impact on the whole product, due to the good LCA of the recirculated materials. These aforementioned data gaps were also present in the development of foam-based coolers, and in order to close them and detect a suitable recycling route, preliminary tests were conducted to investigate different process routes for existing cooling systems in industry as benchmarks. They differ mainly in the previous disassembly and the different shredding machines.

The products mentioned above were studied to investigate a suitable route of the conventional cooling structures. Also to support those investigations with performance data in order to detect a preferred variant, which can then be analogized to the foam-based coolers, or compared with the final process so that the life cycle assessments can be compared. The energy requirements of the process routes were measured using in-machine technology.

Based upon the recorded data, the route with an granulator used for shredding the scrap emerged as the most energy-efficient and thus the most environmentally friendly. It is true that the route with prior disassembly was also promising, as this increased the degree of recycling. However, this was neglected for further investigations, since no foam-based complete structures are yet available and thus no disassembly can take place.

Since, among other things, cooling structures made of coated copper foam -based on polyurethane (PUR)- are to be used and these structures require the greatest development effort, this process was transferred to these metallic foams in a first step. It was found that only 19.41% of these foams were decoated. This means that only about one fifth of the total copper on the surface could be removed and separated. This was done by air separation and density sorting using the float-sink method, which works by adjusting the density of a fluid, causing the copper to sink and the PUR to rise. The exact proportion was determined using the formula:

$$Degree\ of\ decoating = \frac{Mass\ PUR\ in\ light\ fraction}{Mass\ PUR\ in\ Input\ material} \times 100$$

The weight of the PUR in the input material was measured by the supplier before coating and the weight of the PUR in the light fraction, was determined by X-ray fluorescence analysis. It must be assumed that the PUR in the heavy fraction is still bound to the copper, as it cannot be separated out.

Based upon the results of the preliminary tests, a suitable process route must be developed in further investigations that significantly increases the degree of decoating. In addition, the inputs and outputs of the life cycle assessment must be presented in more detail in the future so that no CO2 emitter is omitted.

Summary

In conclusion, the correlating results from simulation and testing already demonstrate improvements in cooling performance by using the stochastic foams used initially. The issue of LCA and recycling needs to be addressed anew for the process to be developed, as commercially available methods do not produce the desired effect.

Overall, the current results are a pointer in the right direction and reveal not only great potential but also a need for action, especially with regard to the implementation of ecological specifications in the initial development stages of a new product. Furthermore, the use of open-cell metal structures for cooling technology, among other applications, is unstoppable, although it is clear that stochastic structures are only the starting point for the development of application-specific structures due to their limited design capability. First approaches to overcome that issue are shown.

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