Insect Wing Inspired Design and Manufacturing of Multifunctional Automotive Applications Using Stereolithography and Subsequent Short Carbon Fiber Reinforcement

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Abstract. An insect wing is characterized by an extremely lightweight but nevertheless strong cellular structure and represents a recurring and widespread solution in nature. In addition to its lightweight design, the vein-like structure is also responsible for the control and nutrient supply. A transfer of this multifunctional approach from nature offers new possibilities in the design, construction and production of extremely lightweight, yet fault-tolerant structures. To realize this principle for technical applications, additive manufacturing via the stereolithography process (SLA) and subsequent infusion with a suspension of epoxy resin and carbon short fibers is used. In order to obtain reproducible production results, the infusion takes place on a therefore developed test rig. To demonstrate the potential of this process, a conventional automotive side exterior mirror is topology-optimized based on the insect wing design rules. During the experiments, 30 wt% carbon fibers (CF) with a mean length of 80 µm can be processed, which results in an increase in stiffness at the same tensile strength compared to a solid polymer structure. In order to achieve electrical conductivity of the structural framework, carbon nanotubes are added to the infusion suspension. As a result, a reduction in weight and assembly effort is achieved by the multifunctional insect wing design.

J. Rieser et al. (Eds.): *Proceedings of the Munich Symposium on Lightweight Design 2022*, pp. 28–39, 2023. https://doi.org/10.1007/978-3-031-33758-1_3

Keywords: Additive manufacturing · Stereolithography · Short fiber reinforcement · Topology optimization · Bionics

1 Background and Motivation

In this approach, biological principles are used and transferred to technical applications in order to realize multifunctional lightweight constructions.

The insect wing is chosen as a model from nature, as it represents a very common solution in the insect world.

In this project, the structure and functions of the insect wing are to be transferred to an automobile side exterior mirror. An exterior mirror consists of a large number of individual components and must comply with a wide range of requirements such as aerodynamics, structural rigidity and assembly effort.

1.1 Multifunctional Insect Wing

An insect wing is characterized by an extremely lightweight but nevertheless strong cellular structure and represents a recurring and widespread solution in nature. The typical structure is shown in Fig. 1. It is characterized by struts in the longitudinal direction and transversal stiffeners. A thin membrane of approx. 1 μm thickness is stretched between the resulting cells, forming the aerodynamic surface. In addition to its lightweight design, the vein-like structure is also responsible for the control and nutrient supply. For example, the trim tank on the outside of the wing can be controlled via the structure.

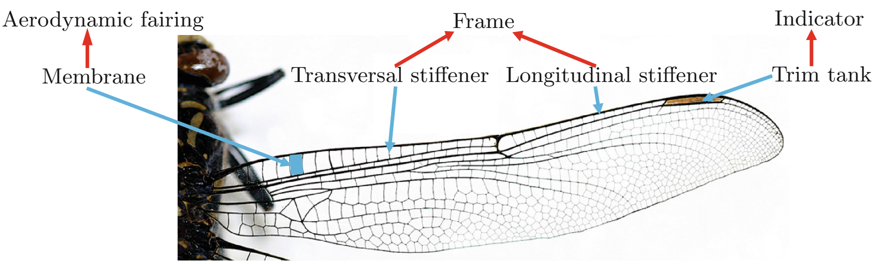


Fig. 1. Insect wing functions (adapted from [1])

These elements and properties of the insect wing are then transferred to the automobile exterior mirror. The frame will be represented by the transversal and longitudinal stiffeners. The membrane between the cells provides the aerodynamic fairing around the structure. The structure itself is to be made electrically conductive in order to contact an indicator.

1.2 Goal

The problem with bionic structures is that they usually have a complex geometry that is difficult or impossible to produce by conventional manufacturing technologies. Additive manufacturing processes can solve this problem. However, the mechanical properties of polymer-based processes are limited and metal-based processes are expensive.

Therefore, a novel hybrid manufacturing process is used and further developed in the following [2]. In this manufacturing process, Stereolithography (SLA) is used to produce the outer shell structure of the part. The resulting hollow structure is then infiltrated with a carbon fiber (CF) thermoset suspension in order to improve the mechanical properties.

The goal of this project is to achieve aerodynamic, mechanical and electrical properties simultaneously, in the sense of a multifunctional insect wing.

2 Topology Optimization and Design

Topology optimization is used here to generate load-appropriate bionic structures as a basis for the design. This is a numerical method based on the FEM for generating design proposals in the early stage. The starting point is the available design space of a component as well as various structural, but also manufacturing constraints. The result of the topology optimization is an optimal material distribution within the design space. Typically, these are truss-like structures as required for the manufacturing process.

The process of the mirror design is shown in Fig. 2. The design space of the mirror is created by filling the outer geometry and then removing the various functional parts such as the mirror glass and adjustment motors. Areas of the exterior mirror that serve as functional surfaces or to mount screws are separated as nondesign space so that no material can be removed here during optimization. The 0.1 mm thick outer cover made of PETG is modelled with shell elements and bonded to the outer surface of the design space. Mirror glass and adjustment motors are represented in the model in a simplified way with mass elements.

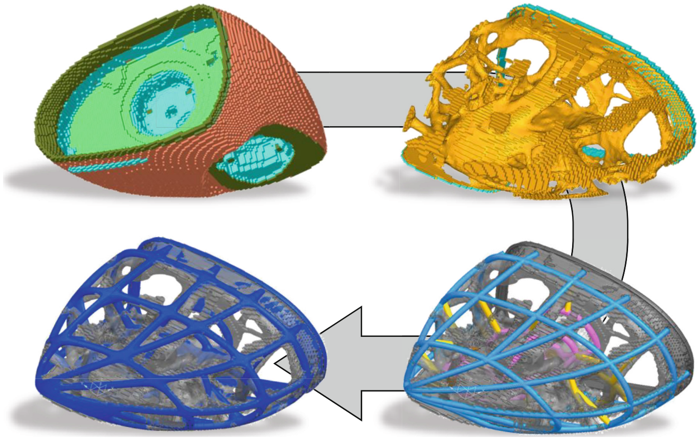


Fig. 2. Design process

The novel manufacturing process discussed here leads to a hybrid material consisting of structures with a fibre-reinforced and thus anisotropic material in the core, and a shell structure made of isotropic material. Since the load paths are not known at the beginning of the topology optimization, the orientation of the fibres and the material distribution between the core and the shell structure cannot be determined. This circumstance makes it necessary to represent the design space with a homogenized isotropic equivalent material model. The material properties are estimated with a representative circular cross-section of $d = 4$ mm inner and $D = 6$ mm outer diameter and thus 55% photopolymer and 45% carbon fiber thermoset suspension consisting of 30 wt% CF via a mixing rule.

Different load cases are considered in the topology optimization. These are subdivided into operating loads like various accelerations, the aerodynamic pressure distribution on the outer surface and other misuse loads and substitute loads for consideration of the crack stop function. A direct consideration of the desired crack stop function is not possible with common topology optimization methods, as it is a component behaviour after initial failure. However, the topology optimization is based on a linear static simulation without failure. As a substitute, a dummy load case is therefore introduced in the form of individual forces acting normal to the outer surface in a 50 mm grid. This load case provides regular, redundant load paths to the cover of the mirror, which can stop cracks.

The manufacturing process has some fundamental constraints, especially with regard to the infusion of the suspension, which can only be taken into account to a very limited extent in the topology optimization. The minimum wall thickness of the structure can be specified in the topology optimization. However, as already mentioned, no distinction can be made between suspension and shell structure. Furthermore, no influence can be exerted on the cross-sectional shape of the channels or their connecting nodes to each other. Such processrelated restrictions must then be considered when transferring the result of the topology optimization into a CAD design.

Bionic, free-form structures often prove challenging to classical CAD design approaches. In most cases, the main goal is to create one or more geometrical bodies that meet all structural, functionality, package and manufacturability requirements they are presented with. Since manufacturability highly depends on the chosen process, the novel hybrid manufacturing method plays an integral part in the decision making. The end product of the design process for a hybrid structure, as discussed in this paper, has to meet the following requirements:

- Hollow base structure with a dual function as an injection mold
- Channel cross section primarily circular for stability during the injection process
- Minimum channel cross section diameter to allow suspension flow during the injection process
- Maintain minimum wall thickness for stability during the injection process
- Smooth transitions and node areas for unobstructed suspension flow
- Provide multiple cavities for galvanic isolation

To meet all goals a hybrid design approach is chosen, which combines the classical CAD design tools with a non-uniform rational basis spline (NURBS) surface based method.

Widely used for 3D design in the entertainment industry, as well as for interpreting topology optimization results for additive manufacturing, NURBS based design is highly efficient in the creation of smooth surfaces and organic structures, but proves challenging when hard targets, such as exact wall thicknesses or cross section diameters have to be met.

At first, all attachment surfaces, including the outer shell geometry are designed with a classical approach. Then, a network of splines and tubular sections is created in accordance with the final topology optimization result, which serves as a temporary reference structure for the next design phase. The diameters of the tubes are determined by the target cross section dimensions and can still be modified easily. In the second design phase, the reference structure is manually translated into several NURBS-based solid bodies. The primary body represents the filled geometry, while the secondary bodies represent the suspension in two galvanically isolated cavities. In the final step of the hybrid design approach, all previously created interface and attachment areas are combined with the primary NURBS-based body and the suspension bodies are subtracted to create the hollow base structure, before sprue positions are determined and added. The step from reference structure to final structure is illustrated in the bottom half of Fig. 2.

The used hybrid design approach combines the efficiency of NURBS-based surfaces with the dimensional stability and reliability of classical CAD modeling methods and proves to be suitable to design hybrid structured parts, as presented. To increase design efficiency and allow for a more widespread use, improvements to the software capabilities are required. Especially the separate creation of the suspension bodies is one of the key hurdles in efficiently creating NURBS-based, hollow structures.

A simulative validation of the final design has not been carried out here. Especially for the prediction of the strength, much more complex material models with corresponding underlying material tests are necessary. The local material properties strongly depend on the distribution and orientation of the fibres of the suspension. For an accurate prediction of the component properties, a coupled filling and structure simulation would therefore be necessary. There are similar process chains that could be built on in the field of fibre-reinforced thermoplastic injection moulding.

3 Manufacturing Technology

The process to be carried out for subsequent short fiber reinforcement is shown in Fig. 3.

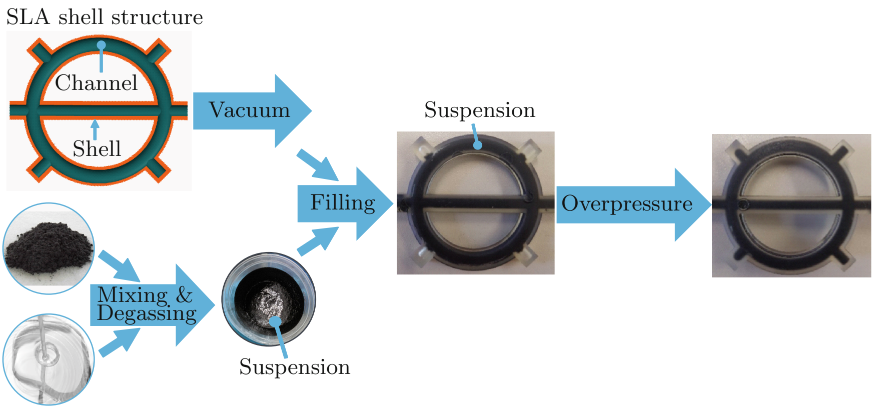


Fig. 3. Process to execute

The baseline is the topology-optimized shell structure, which is produced with the SLA process. This structure needs to be evacuated. The second step is the mixing of the carbon short fibers with the infiltration resin with simultaneous degassing. To achieve high mechanical properties, a homogeneous, void-free suspension is essential. The suspension is then infiltrated into the evacuated shell structure. Pressure is applied to completely fill undercuts. The suspension then cures in the structure.

In order to carry out this process as reproducibly, error-free and semi-automated as possible, a test rig developed for this purpose is used. It is shown in Fig. 4.

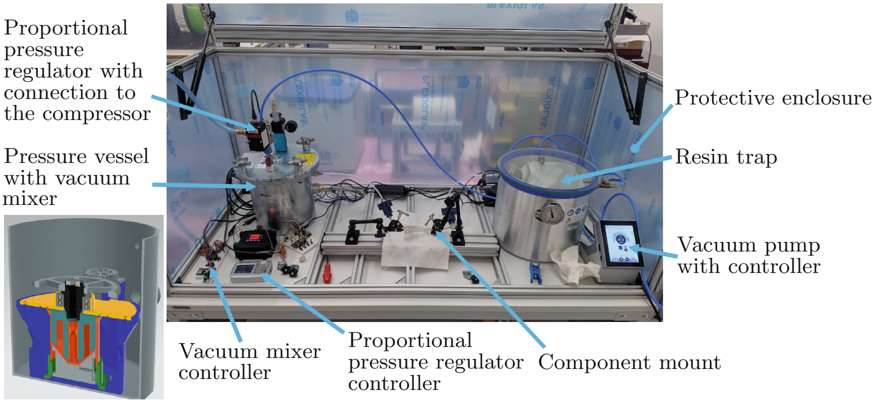


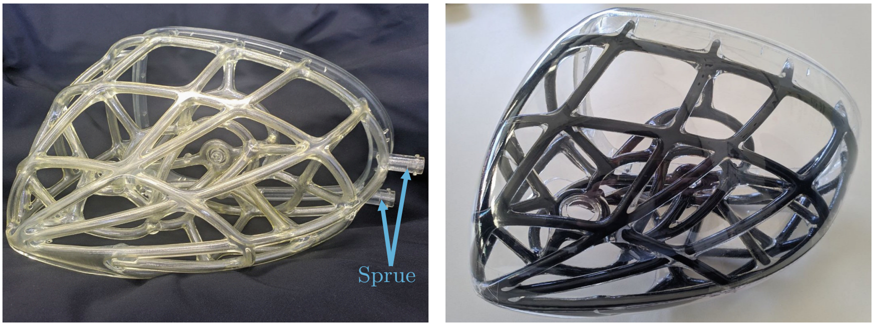
Fig. 4. Test rig for component infiltration

The central part of the system is a pressure vessel, in which there is an apparatus for mixing and degassing the suspension. The pressure inside the vessel can be controlled via a proportional pressure regulator. From the mixer, the suspension can be conveyed directly out of the vessel by pressure differences through hoses. This avoids decanting, which would cause air to get into the suspension. The component to be infiltrated is mounted on the test bed and the hoses are connected to it via sprues. From the left side the hose with the suspension supply comes from the pressure vessel and on the right side the hose goes to the vacuum chamber.

For the infiltration of the parts, the low-viscosity epoxy resin Epikote RIMR 135 is used with the hardener RIMH 137 in a ratio of 100 to 30 parts by weight. The fibers chosen are Sigrafil C M80-4.0/240-UN (SGL Carbon SE) with a mean length of 80 µm and no sizing.

With this process technology in combination with this resin system and these fibers, fiber contents of up to 30 wt% can be reliably mixed and conveyed.

For the side exterior mirror topology optimized in Sect. 2, the hollow structure fabricated with SLA is shown in Fig. 5a. This part is infiltrated with a suspension consisting of 30wt% carbon fibers. A thermoformed PETG cover is then bonded to the structure, which serves as an aerodynamic fairing. The finished side exterior mirror can be seen in Fig. 5b.



(a) (b)

Fig. 5. Production and infiltration of the side exterior mirror. (**a**) Hollow structure, (**b**) Finished part

4 Results

In order to determine if the structural requirements are met, the following mechanical and electrical tests are carried out.

4.1 Mechanical Properties

In order to verify the mechanical properties, tensile specimens are produced via SLA in accordance with DIN EN ISO 3167. The cross-sectional area of the test area is round with a diameter of 6 mm. These specimens are made both solid from the photopolymer BASF RG35 and hollow with a channel diameter of 4 mm. This diameter corresponds to the smallest cross-section that can be infiltrated reliable, and a wall thickness of 1 mm is minimally required to safely withstand the pressure differences during the filling process. These values also serve as boundary conditions for the topology optimization in Sect. 2.

Figure 6 compares the results of the tensile tests with solid material and 30 wt % carbon fiber filling. It shows that the short fiber reinforcement increases both the Young's modulus by 189% and the tensile strength by 16%. The elongation at break, on the other hand, decreases by 79% due to the higher stiffness of the carbon fibers. The numerical values can be found in the average in Table 1.

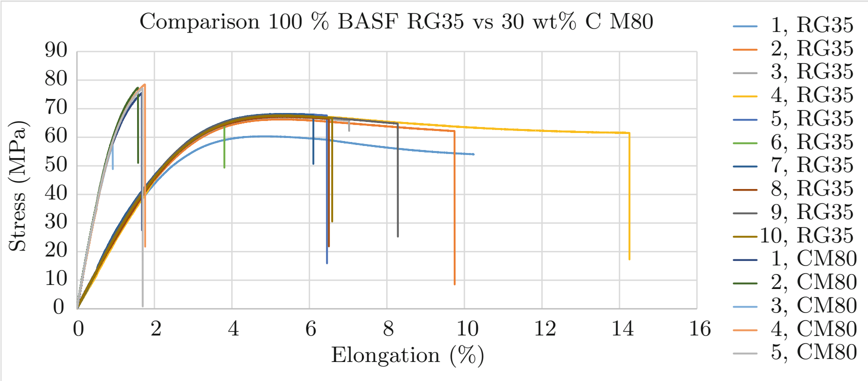


Fig. 6. Comparison of mechanical properties

Table 1. Comparison of mechanical properties

Parameter	BASF RG35	BASF RG35 + 30 wt% C-fibers	Comparison	
Young's modulus	2.53 GPa	7.33 GPa	Increase by 189%	
Tensile strength	66.5 MPa	77.12 MPa	Increase by 16%	
Elongation at break	7.9%	1.67%	Decrease by 79%	

4.2 Electrical Conductivity

In the sense of a multifunctional approach, the structure should fulfill not only mechanical but also electrical tasks. Therefore, LEDs shall be contacted directly via the structure. According to [3] the percolation threshold depends on the aspect ratio of the short carbon fibers. The fibers used have a diameter of 7 µm, resulting in an aspect ratio (AR) of 11.43. This is too low for the formation of a sufficiently conductive network with the maximum fiber weight fractions that can be processed. Therefore, it is necessary to add carbon nanotubes (CNTs) as conducting filler. These have according to the technical data sheet an AR of 2000 − 10000. Although the addition of CNTs significantly improves the electrical conductivity, the high AR also causes the viscosity of the suspension to increase very fast. As a compromise between processability, mechanical and electrical properties, a content of 20 wt % carbon fibers and 2 wt % CNTs is therefore chosen.

For the exterior mirror demonstrator, two channels are separated from the rest of the structure. These channels are filled with the CNT modified suspension. The contacts of the LEDs and the power supply are glued directly into the structure with silver epoxy glue. The positions of the conductive channels and connections are shown in Fig. 7.

The contacting and power supply of the LEDs through the structure works in principle with this method, but the resistance in the range of 30 KΩ is very high, so that the luminosity would be insufficient for traffic applications.

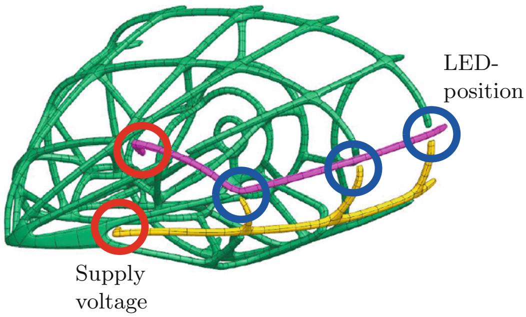
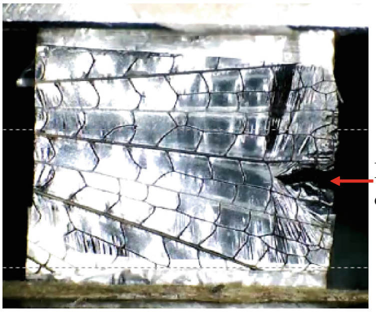


Fig. 7. Path of the electrically conductive structure

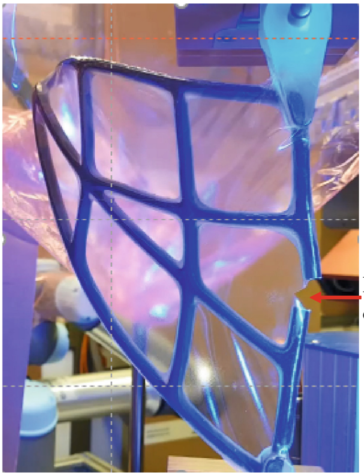
4.3 Crack Stop Function

For an insect, the cellular structure of the wing is of great importance, since damages and cracks in the membrane remain restricted to one cell, thus ensuring the ability to fly [4]. As a transfer of this principle into the technical application, a part of the exterior mirror is used and the surface of the structure is covered with a thin adhesive foil. In addition, an initial crack is added in the middle of this part. Via an SLA printed individual connection, this build-up is clamped into a tensile testing machine and then pulled apart. The experimental setup is shown in Fig. 8a. for an insect wing and in Fig. 8b for the exterior mirror section.

As result, the technical replica behaves in principle similar to the insect wing. The crack grows over the cell and remains locally confined to it. However, due to the significantly higher stiffness of the carbon fiber-reinforced struts respectively the resulting lower elongation at break, the structure fails before the crack reaches the end of the cell. For technical applications such as the side exterior mirror, this characteristic can be used, for example, that in the event of a stone impact, only a hole appears in one cell, but the overall function of the mirror is still maintained.



(a) Insect wing [4]



(b) Section of the exterior mirror

Fig. 8. Demonstration of the crack stop function

5 Conclusion and Outlook

It has been shown that the structure and function of an insect wing can be transferred to the technical application of an automotive side exterior mirror. For this purpose, the mirror was successfully topology-optimized and designed for the subsequent fiber reinforcement process. With the test rig set up, components can be infiltrated reproducibly and reliably with up to 30 wt% carbon short fibers. Thus leading to an increase of the Young's modulus by 189% and the tensile strength by 16% compared to the pure photopolymer. The electrical conductivity of the structure was realized by adding CNTs, however, the resistance is still high. By covering the structure with a thermoformed PETG film, a cellular, damage-tolerant structure was created.

This allows the production of topologically optimized, multi-functional lightweight structures in a short fiber composite design. Aerodynamics, stiffness and electrical conductivity are achieved simultaneously in the sense of a multi-functional insect wing, which allows a reduction in weight and assembly effort.

Further research should focus on improving the test rig for reliable processing of higher fiber content. In addition, it would be useful to match the resin systems (photopolymer and infiltration resin), coatings and fibers (length, diameter) to each other to improve the reinforcement effect. It is also possible that a matched system simultaneously increases electrical conductivity.

Another research aspect is the development of a process simulation, e.g. to make structural-mechanical forecasts by predicting the fiber orientation in the structure.

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