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Process Chain of Injection Moulding And Additive Manufacturing For Hybrid Parts

Johann Schorzmann[1], Daniel Pezold[1] , Jan Kemnitzer[2],
Alexander Kalusche[3], Frank Döpper[1,2]

[1]*University of Bayreuth – Chair of Remanufacturing and Manufacturing Technology, Bayreuth, Germany*
[2]*Fraunhofer Institute for Manufacturing Technology and Automation IPA, Bayreuth, Germany*
[3]*Acad Group GmbH, Heilsbronn, Germany*

Abstract

To achieve lightweight properties, a process for the local reinforcement of injection-moulded parts using additive manufactured continuous fibre reinforced inserts was developed. The process is based on the additive manufacturing (material extrusion) of semi-finished products (inserts) made of pre-impregnated continuous fibres, which are inserted in a defined position of the injection mould and then over-moulded with a compatible polymer matrix. Due to the manufacturing method of the inserts, a material, form and frictional bonding between the fibres and the polymer matrix can be realised. By choosing a specific positioning of the inserts resp. the continuous fibres, one can achieve a significant lightweight construction potential and the targeted elimination of process-related weak points such as weld lines of the injection-moulded parts.

A virtual development process using digital product development tools were applied for the construction of a concrete application example. A combination of topology optimisation and finite element analysis (FEA) was used to determine the load- and material-optimised design. For the simulation and optimisation of hybrid parts a new method of virtual development and definition of material models for additively manufactured components was developed. The validation of the process chain for hybrid parts was carried out using a test setup that represents real load situations of an automotive part. The technical analysis of the hybrid part showed a weight saving of 19.5% compared with the reference part. Regarding the critical load case (load from above), a 38.1% lower deformation was achieved. The specified maximum load and deformation limits were maintained in the use case. In addition, in the weld line area malfunction was avoided by the continuous fibre-reinforced insert.

Keywords

Injection moulding; additive manufacturing; hybrid part; continuous fibre reinforced inserts; topology optimisation

1. Introduction

Over decades, numerous manufacturing processes have been developed that enable the processing of polymers. Injection moulding has established itself as a standard process in industrial applications for the production of polymer parts. Due to the high level of existing know-how and the optimal control of the processes in the field of injection moulding, this manufacturing process enables the high-quality and costeffective production of polymer parts in large quantities (large-scale production). The wide range of available materials also makes injection moulding interesting for the industry. However, the large number of advantages is offset by a number of disadvantages. The strengths and stiffness's when using thermoplastics are low in relation to metal materials and are also stress-dependent [1]. Due to these circumstances, these injection-moulded parts are not suitable for high stresses, which means that the weight advantage of metal materials is no longer decisive.

To leverage more of the lightweight potential of injection-moulded parts, it is necessary to improve their mechanical properties. Technically feasible approaches already exist, in which unfilled plastics are substituted in the injection moulding process by short (0.1 – 1.0 mm) or long (1.0 – 50.0 mm) glass fibre reinforced polymers. However, the use of significantly better reinforcing continuous fibres (endless) is not feasible here, as these fillers cannot be processed in injection moulding. Therefore, there is still a need for research in the case of local stress and simultaneously required minimum weight. [1] For these requirements, however, one alternative is to integrate continuous fibre into an injection-moulded part using an additional manufacturing process. In this case, additive manufacturing can be used to significantly improve the mechanical properties of polymer parts and utilizing the geometrical freedom to locally reinforce the polymer part [2-8].

Accordingly, the aim of this scientific work is to develop a concept to improve the mechanical capabilities and at the same time save material and reduce weight of an injection moulded part by inserting an additive manufactured continuous fibre reinforced part. For this purpose, a virtual product development process is applied.

2. State of the Art

Insert technology is one way to open up further lightweight potential and at the same time improve the mechanical properties of an injection-moulded part. Here, the designing engineer can react to the local stresses and reinforce the stress hotspots in the injection-moulded part by locally positioned inserts. In polymer processing techniques usually, the inserts are made of metallic materials. Using metal inserts can create a friction or form bond and for material bonding a post processing step has to be applied. However, when the part volume is small, it is difficult to transfer the load to the metal. Following the example of long glass fibre reinforced injection moulding, inserts made of continuous fibre reinforced polymer composites offer new manufacturing possibilities. Thus, mechanical properties can be significantly increased at the areas subjected to the highest local stresses. For example, local reinforcement offers the possibility of reducing ribbing, wall thicknesses, and the long glass fibre filler content, which leads to further material and weight savings [1]. To realize the material and weight savings, continuous fibres can be integrated into an injection-moulded part via an additional upstream manufacturing process. The additive manufacturing technologies offer new approaches for this purpose.

The additive manufacturing process **of** material extrusion (MEX), which uses filaments as semi-finished products for producing parts, is increasingly developing from a manufacturing process for prototypes to a manufacturing process for end use parts. Similar to other polymer processing methods, mechanical properties of the manufactured parts can be further enhanced by MEX through the addition of fillers such as nanomaterials, particles or short fibres to the used filament. These composite filaments are characterised by high mechanical properties at low weight and very good functionality. However, the mechanical properties of short fibre reinforced composites produced by additive manufacturing are still more anisotropic with composites produced by conventional methods, depending on the orientation of the additive manufactured part and the processing parameters of the additive machine. For the production of continuous fibre reinforced thermoplastic parts, MEX promises to be an alternative to conventional process chains, since no cost-intensive equipment, such as tooling or autoclave, is required [9, 10]. In general, the additive manufacturing process MEX for producing continuous fibre reinforced polymer parts uses a multi-material approach. Two filaments (continuous fibre reinforced filament with polymer matrix and an unfilled polymer filament) are heated up and extruded layer by layer in order to manufacture a continuous fibre reinforced polymer part (see Figure 1).

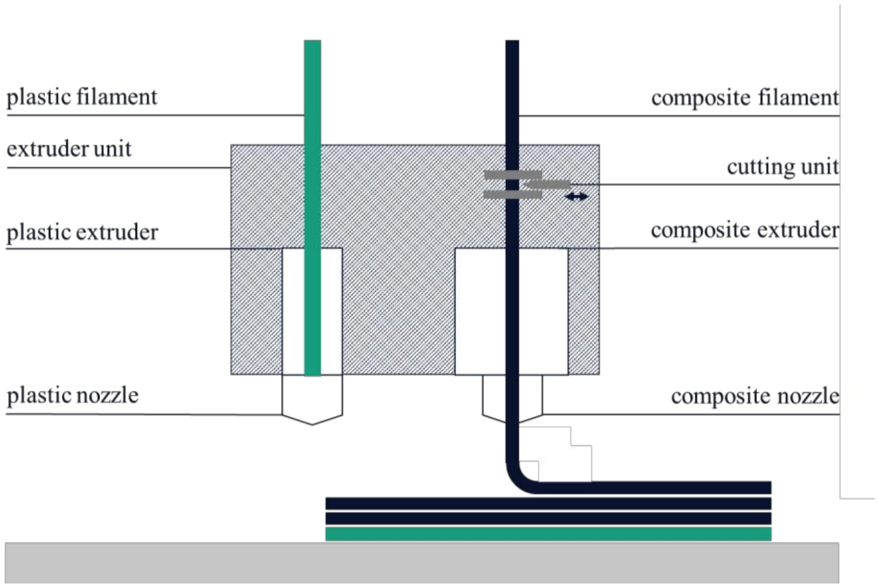

Figure 1: Schematic structure of the Additive Fusion Technology [11]

Therefore, the geometry of the additive manufactured continuous fibre reinforced polymer inserts can be individually and digitally adapted to the exposure path. In general, when processing the continuous fibre filament, their dimensions must be taken into account, since their stiffness means that they cannot be processed in the MEX in the same way as the unfilled polymer filaments because of the lower bending radius in comparison to the unfilled polymer filaments.[11]

9T Labs' Additive Fusion Technology (AFT) uses the strategy of upstream co-extrusion process for composite filament production and dual extrusion method in the manufacturing process (Figure 1). The composite filament's fibre volume content of 60% is very high compared to others available on the market. [11, 12]

3. Methodology

The objective was to improve a reference part from the automotive industry: armrest. To increase the strength combined with a simultaneous reduction in weight, further development in design, simulation and production technology were necessary. The standard reference part was made of a long glass fibre reinforced thermoplastic using an injection moulding process. The approach pursued to increase strength was the use of continuous fibres, which could not previously be introduced or processed in the injection moulding process. The continuous fibres were integrated in an upstream production stage. Therefore, in order to achieve an improvement in strength, locally additively manufactured continuous fibre reinforced polymer inserts were implemented in the reference part. Additive manufacturing could be used to individually manufacture filigree structures from pre-stretched continuous fibre reinforced polymer filament with a rough surface without the need for tools, which was not possible using previous manufacturing technologies. The rough surface in case of the high fibre content is used for better bonding in injection mould and the continuous fibre reinforced insert. The simultaneous weight savings were achieved by using virtual product development tools to design the hybrid part. By identifying the load flow in the reference part, the part could be strengthened at highly loaded locations and material saved at less loaded locations (see Figure 2)

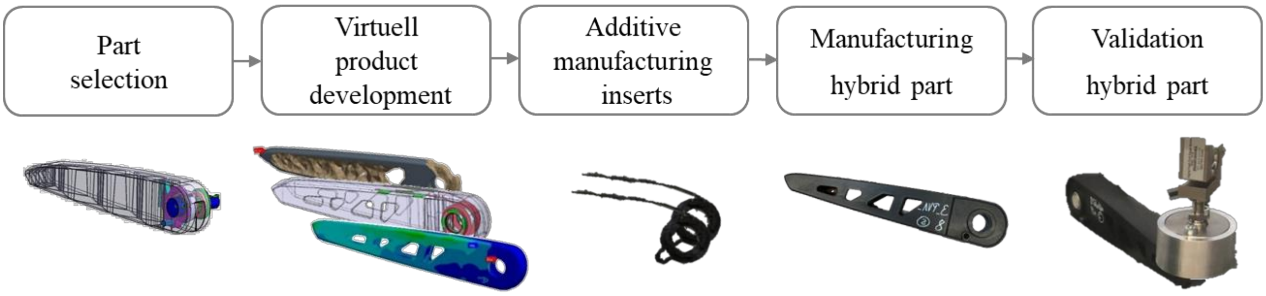

Figure 2: Procedure for the developed hybrid part

In the first step of the process chain for hybrid parts, the boundary conditions of the reference part were defined, which reflected the conditions of use in reality. In particular, the load situation and the mounting conditions of the reference part were to be mentioned as boundary conditions. Based on these boundary conditions, a load-optimised reference part was developed in the subsequent step. A finite element analysis (FEA) and a topology optimisation were carried out to determine the optimum material distribution in the reference part in terms of the load. The reference part was redesigned on the basis of these simulation results. This already enabled an initial lightweight design potential to be raised. In addition, the simulation results served as a preliminary stage for analysing the possible position and alignment of the continuous fibre reinforced inserts.

Before the design of the continuous fibre reinforced inserts could begin, it was necessary to evaluate the position in the injection-moulded part in which the continuous fibre reinforced inserts would be over-moulded and how much space they would take up in the geometry of the injection-moulded part. The shape of the continuous fibre reinforced inserts was restricted by the geometry of the injection-moulded part and should be aligned with the stress distribution in the part [13, 14]. For this reason, the design of the continuous fibre reinforced inserts was based on the results of the FEA calculation, in addition to the restrictions imposed by the space and the manufacturing constraints resulting from the additive manufacturing process. In the material model the anisotropy resulting from the injection moulding process also had to be taken into account. [15]

The next step was the virtual development of the hybrid reference part, which consists of two parts: the load-optimised injection-moulded part and the continuous fibre reinforced insert. In this stage of the development various virtual product development tools were used to design the hybrid reference part. An iterative process, combining FEA, topology optimisation and redesign, was run through to determine a load-optimal design for the hybrid reference part. The focus was on further weight savings by optimising the injection-moulded part and determining the geometry and optimal number of layers of the continuous fibre reinforced inserts. The strength of the hybrid reference part was simulatively validated using FEA For the simulation of the mechanical behaviour of the continuous fibre reinforced insert a non-linear anisotropic material model was used. (see Figure 3)

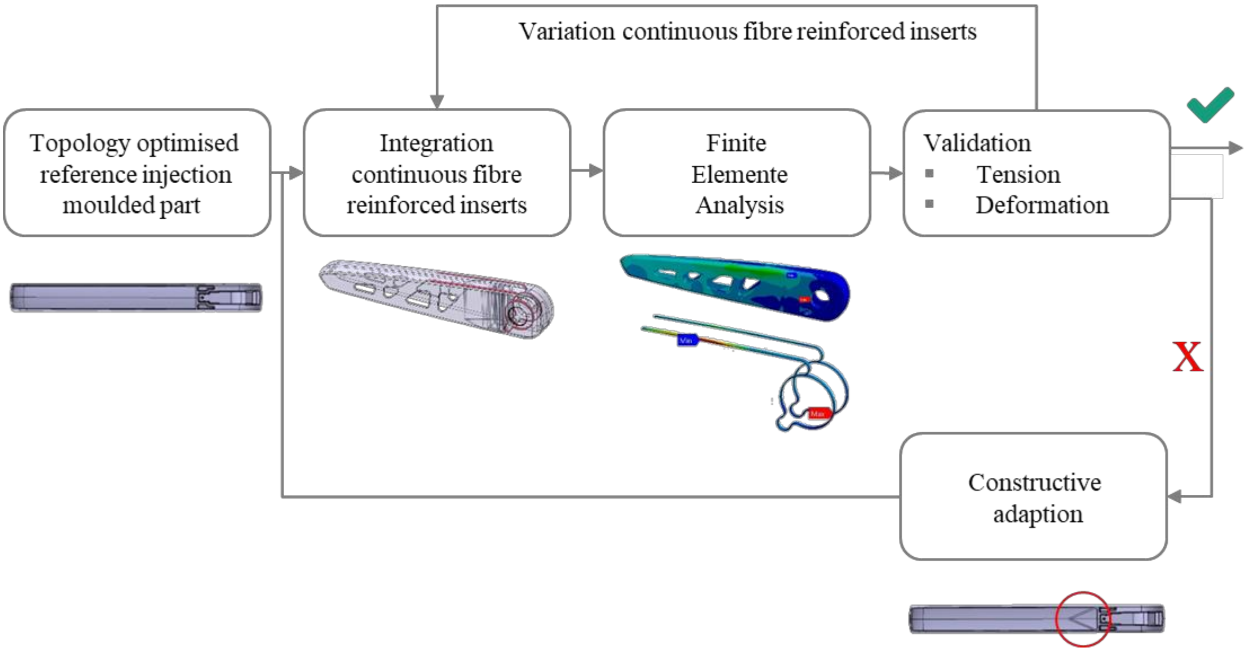

Figure 3: Procedure of virtual product development of the hybrid part

The optimum resulted from the cost aspect, whereby the size of the continuous fibre reinforced inserts was predominant, the insert costs were significantly higher than those of the injection-moulded part. Therefore, the optimal number of layers was primarily determined. The number of layers was considered optimal if the hybrid part reached the minimum safety factor and a further increase in the number of layers would not result in a significant improvement in strength or a reduction in the safety factor observed.

At the beginning, a topology optimisation of the reference part, which was normally manufactured by injection moulding, was carried out. The results of the topology optimisation were used as an indication of the areas where material and corresponding weight could be saved. Subsequently, the newly designed topology optimised hybrid part had to be validated by performing FEA calculations for the critical load cases. The boundary conditions were the same for all FEA calculations. The safety factor of the topology optimised part was used as the primary decision criterion for evaluating the strength of the hybrid part. Here a minimal safety factor had to be achieved so that the material did not fatigue under loading cases. Especially fibre fracture have to be prevented . For the further procedure for integrating the continuous fibre reinforced inserts, the determined load optimised structure served as the design basis of the hybrid part. The results of this FEA calculation were used to locate the optimal positions for the continuous fibre reinforced inserts.

Due to the load distribution and the formation of weld lines in the part, the area of the armrest's bearing surface and the area of the assembly suspension on which the armrest was mounted to the car seat were identified as critical. Therefore, the continuous fibre reinforced inserts were used in these areas to further reinforce the part. The main objective was to ensure that the load flow when the armrest was under stress was primarily directed into the continuous fibre reinforced inserts and thus into the fibres, which leaded to the load relief of the topology optimised structure. The next step was to determine the design of the continuous fibre reinforced inserts. The design was limited on the existing volume of the topology optimised injection-moulded part and the manufacturing restrictions of the continuous fibre reinforced additive manufacturing process (layer height 0.27 mm, fibre width: 1.1 mm). In the first instance, the optimum number of layers of the continuous fibre reinforced inserts were determined, starting with a minimum number of layers of two. Subsequently, the structure of the hybrid part was validated by means of renewed FEA calculations. This involved checking whether the topology optimised structure together with the continuous fibre reinforced inserts (hybrid part) was sufficient for the existing loads. In particular, the focus here was on the continuous fibre reinforced inserts, where it was important to avoid fibre breaks so that the load flow continued to be directed into the fibres. If the FEA calculation of the topology optimised hybrid part results insufficient safety factors the continuous fibre reinforced inserts were primarily redesigned by increasing the number of layers. If necessary, many iteration loops had to be performed until the optimum number of layers was achieved and the requirements of the topology optimised hybrid part could be observed simultaneously.

However, if the threshold of the safety factors and the total deformation could not be exceeded or not reached and if there was no more space to increase the number of layers of the continuous fibre reinforced inserts, a constructive adaptation of the topology optimised part had to be carried out. This meant that too much material was removed in the first step of the topology optimisation and the continuous fibre reinforced inserts could not compensate loss of strength due to the material reduction.

Therefore, an improvement of the stability of the topology optimised hybrid part had to take place by a constructive modification of the topology optimised structure. At this point, the iteration loop for determining the optimal number of layers and observation with the requirements for the topology optimised hybrid part started all over again. If, however, the optimal number of layers and the requirements for the part were achieved, it might also be possible to save material and weight by reducing the material additionally. The weight saving was to be chosen as the termination criterion of the iteration loop. As soon as no significant weight advantage could be achieved by the constructive modification of the topology optimised structure, the iteration loop was terminated and the continuous fibre reinforced insert did not result in a significant improvement of the strength. The procedure was characterised by numerous iteration loops until a result could be achieved. These iteration loops were carried out until the constructive redesign of the topology optimised structure showed no weight advantage compared to the reference part.

Following the virtual validation of the topology optimised hybrid part, the physical validation procedure of the process chain for hybrid parts was carried out. After the continuous fibre reinforced inserts had been additively manufactured, they were inserted into specially provided and appropriately designed cavities in the injection mould. The inserts were manufactured from a continuous fibre-reinforced polymer filament, composed of 60 wt.-% 3K fibre filament count tows and 40 wt.-% Polyamide 12 polymer. Then the continuous fibre reinforced inserts were over-moulded with polymer (Polyamide 66 with 30 wt.-% glass fibre content). Otherwise, the process did not differ from the conventional injection moulding cycle. It was essential for a good injection moulding result that the continuous fibre reinforced inserts were suitably fixed, because otherwise the complete encapsulation by the melt was jeopardised and warpage could occur [1].

Furthermore, additional criteria had to be observed when the polymer melt flowing around the inserts. Ideally, the position of the continuous fibre reinforced inserts should be chosen advantageously in relation to the weld line positions in order to avoid air inclusions. Therefore, the flow of the melt around the continuous fibre reinforced inserts had to be optimised. In addition, the reorientation of the long glass fibre of the injection moulding material had to be taken into account, which occurred when flowing around the inserts by the polymer melt. The long glass fibres aligned along the continuous fibre reinforced inserts and enveloped these. The flow direction of the melt also helped pre stretching the continuous fibres in the load direction [4].

In the last step of the development several selected prototypes of the hybrid reference parts were manufactured, which have different modifications of the continuous fibre reinforced inserts (path design of the continuous fibre or the number of layers of the inserts). In this process, continuous fibre reinforced inserts were additively manufactured from a composite filament using the continuous fibre reinforced MEX process AFT. The continuous fibre reinforced inserts were placed in an injection moulding tool and over-moulded with long glass fibre reinforced thermoplastic. By attaching polymer distance keepers to the continuous fibre reinforced inserts, it was possible to ensure that they hold their position in the injection mould. Finally, the hybrid parts were validated by means of a test set-up that reproduced the real load situations in the mounted state. This was used to validate the results from the simulation and to qualify the development process for series production.

4. Results

The technical analysis of the hybrid part compared to the reference part showed a 19.5% reduction in weight in the primary objective of weight saving. In the first critical load case (load from above), a 38.1% lower deformation was achieved (see figure 4). The specified maximum load and deformation limits resulting from the application were adhered too. In addition, failure in the area of the weld line could be avoided due to the continuous fibre reinforced inserts.

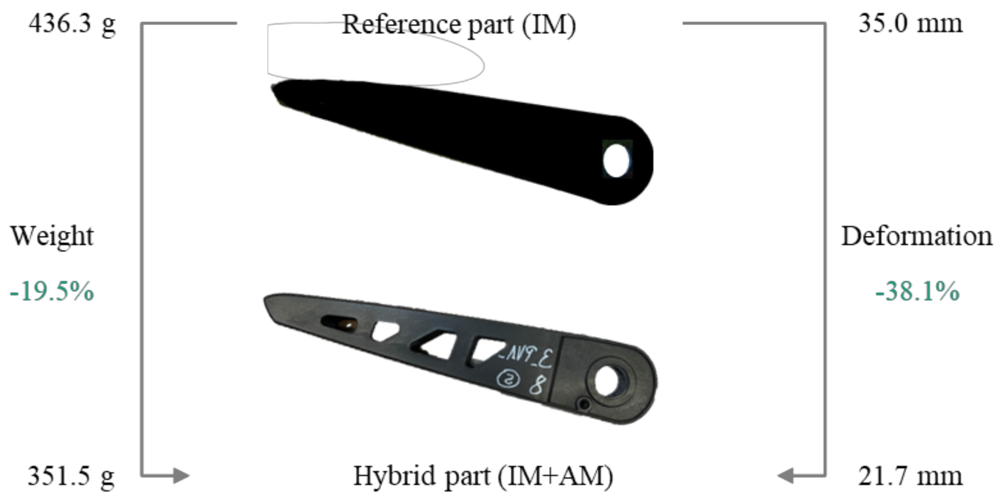

Figure 4: Comparison of reference part (IM) and hybrid part (IM + AM)

During the simulations, it was observed that an increase in the number of layers of the continuous fibre reinforced insert up to an optimum has a positive influence on the increase in the strength of the hybrid part. Further layer number increases beyond the optimum result in a reduction of the strength. This can be explained by the interlaminar interaction of the individual layers, whereby delamination takes place and the detachment of the individual layers leads to an overall reduced reinforcing effect of the continuous fibre reinforced inserts. The delamination beyond the optimum layer number of the inserts occurs because of the reduced layer bonding during long manufacturing time. The long manufacturing time results in inhomogeneous cooling conditions, which have a negative impact on layer bonding. In addition, the weak point of the weld lines could be compensated by the reinforcing effect of the continuous fibre reinforced inserts. A shift of the fracture points away from the critical area of the assembly fixture to the front area of the armrest was observed. The economic analysis of the hybrid part showed that the costs were still too high for the application in the automotive industry. The value of 5 €/kg additional costs per saved kilogram in the prototypes, which is usual for the automotive industry, was exceeded. However, it is an attractive solution for special solutions in vehicles or for applications in medical technology or the aviation industry.

5. Summary and Outlook

To answer the research question, which focuses on achieving lightweight construction goals in a long glass fibre reinforced injection-moulded part, the concept of continuous fibre reinforcement was developed. The lack of processing possibilities for continuous fibres within the injection moulding process made it necessary to add another manufacturing process to integrate the continuous fibres (process chain for hybrid parts). The continuous fibres were implemented as semi-finished products according to the principles of insert technology. For the production of these continuous fibre reinforced inserts, the continuous fibre reinforced additive manufacturing was selected. An iterative procedure for the virtual product development of a hybrid part could be worked out. Especially the interaction of different tools of virtual product development from design, FEA validation and simulation has an innovative character. Furthermore, it should be critically noted that the anisotropic elastic constants and strengths of the parts and materials for the FEM and simulation were determined by semi-empirical equations, since no reliable material parameters were available from the manufacturers or in the literature. More realistic simulation results can be expected if the anisotropic elastic constants and strengths are determined experimentally by means of tensile tests. In addition, the quality of the simulation results can be increased if there is a better interface between injection moulding and FEM simulation. In this context, further developments of the software are to be made with regard to the consideration of continuous fibre reinforced laminates in the injection moulding simulation according to the principles of insert technology.

Nevertheless, the validation of the hybrid parts showed that the simulation results correspond to the real load situation in terms of strength. In the hybrid parts, a further increase in the mechanical part properties could be achieved by optimising the continuous fibre reinforced inserts. The technical analysis of the hybrid part compared to the reference part showed a 19.5% reduction in weight in the primary objective of weight saving. In the first critical load case (load from above), a 38.1% lower deformation was achieved. An additional adaptation of the injection moulding tool is not necessary for this. In particular, the optimal increase in the number of layers to stabilise the continuous fibre reinforced inserts in the injection moulding tool. Likewise, the strength of the hybrid part can be further increased by compressing the continuous fibre reinforced inserts (improved layer adhesion of the individual continuous fibre layers).

The bonding of the inserts with the injection-moulded matrix of the hybrid part creates a material, form and friction bond without the need of a post-processing step. Whereas with metal inserts only a friction or form bond can be created and for material bonding a post processing step is necessary. This is favoured by a low heat distortion temperature of the polymer matrix of the continuous fibre reinforced inserts, so that the polymer matrix of the continuous fibre reinforced inserts is also melting during over moulding with the long glass fibre reinforced thermoplastic. This results in an atomic bond between the two polymer matrices when the part solidifies.

Considering the economic circumstances of the application in automotive industry the part costs to achieve this weight saving are considered too high, if the acceptable additional costs per weight saved in the automotive industry (5 €/kg) serve as a reference. Therefore, the application in aviation industry in order to substitute metallic parts through hybrid parts can be considered.

Furthermore for more applications the superior thermal and electrical properties of the continuous fibre reinforced inserts can be utilised. Besides the enhancement of mechanical properties and the weight saving potential the continuous fibre reinforced inserts can reduce thermal expansion and increase the thermal conductivity for the application in the optics industry. The high electrical conductivity of the continuous fibre reinforced inserts can also be used to integrate sensors and selective conducting paths in injection moulding parts.

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Biography

Johann Schorzmann (*1991) is a research associate at the Chair of Manufacturing and Remanufacturing Technology at the University of Bayreuth since 2020. He has managed and conducted a number of research and industrial projects in the context of additive manufacturing.

Daniel Pezold (*1988) started working at the Chair of Manufacturing and Remanufacturing Technology at the University of Bayreuth in 2017. In his current position within the group of additive manufacturing, he has the project lead of "Anwendungszentrum 3D-Druck Oberfranken". He is specialized within endless fibre reinforced polymers and High Speed Sintering.

Jan Kemnitzer (*1989) is working at Fraunhofer Institute for Manufacturing Technology and Automation IPA in Bayreuth. He is group leader of the division additive manufacturing and is specialised on the powder bed fusion of polymer (PBF-P) processes.

Alexander Kalusche (*1962) founded and is leading the acad group GmbH in Heilsbronn. Acad group is specialised in rapid fibre reinforced polymer injection molding and is designing polymer parts for the automotive and medical sector.

Frank Döpper (*1970) has been head of the Chair of Manufacturing and Remanufacturing Technology at the University of Bayreuth and the Fraunhofer Institute for Manufacturing Technology and Automation IPA in Bayreuth since 2017.