Additively Manufactured Roof Frame Segment with Local Carbon Fiber Reinforcement

To date, polymer-based additively manufactured structures have failed to gain a foothold in vehicle bodies due to inadequate mechanical characteristics. Now, Audi and Cikoni have presented an approach combining additive manufacturing with carbon fiber reinforcement based on a concept study.

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Additive manufacturing methods allow components to be implemented simply and quickly, which is why this technology is considered the forerunner for producing custom parts and components with exceptional functional integration. No other method enables the manufacture of such complex part geometries beginning with a quantity of just one while eliminating the need to purchase the necessary tools. The comparatively high per-kilo costs of component weight are relativized thanks to eliminating investment in tools and paving the way to elicit additional design potential, above all for smaller and pre-production series batches.

However, implementing a part requiring high-level lightweight design and mechanical performance with additive manufacturing while also meeting economic needs presents a challenge. While common polymer materials for additive manufacturing exhibit high density, they are also restricted in terms of stiffness and stability. Continuous fiber-reinforced fused-layer (Fused Deposition Modeling, FDM) materials are extremely costly and still only allow mechanical reinforcement in the print layer but not three-dimensional component stiffening. Metallic materials for additive manufacturing offer high mechanical characteristics in all spatial directions but are unsuitable for lightweight design applications owing to their high density and are less appealing from a commercial perspective.

> Functional prototypes can be implemented quickly and without any tools.

The AdditiveCarbon process presented by Cikoni represents a promising response to this type of requirements profile. The concept involves a hybrid mindset and design; uniting the advantages of additive manufacturing with the benefits of 3-D winding of continuous fibers. Additive manufacturing is used for molding with a high level of design freedom and minimizing material consumption, with carbon fibers ensuring the desired mechanical performance of the components, processed with little waste and maximum usability directly from the roll and without using any additional tools. This method was used in a concept study for a lightweight design roof frame of the Audi RS5 Coupé Fiber-reinforced Plastic (FRP) roof as presented below.

Simulation as the Starting Point

The design and manufacturing method presented is not just intended to be seen as an option for small-series production, but also paves the way toward implementing functional prototypes and derivatives swiftly and without using tools. This opens up a broad, long-term area of deployment for future applications in vehicle body construction.

The part under consideration is a component of the Audi RS5 Coupé FRP roof with high performance and lightweight design requirements, Figure 1 and Figure 2. The aim is to achieve a lighter component weight compared with the reference structure while maintaining equivalent function. A simulation model of the comparative sizing load conditions of the reference assembly also represents the starting point for the design process in this respect, Figure 3. Structural simulation and numerical optimization can be used to determine the required number of reinforcement windings based on the computed target stiffness, the available installation space and the component performance specification with lower weight. Furthermore, the simulation indicates its optimization along with the volume available for additive manufacturing and its ideal distribution.

To ensure high predictive quality in the structural simulation of continuous fiber-reinforced parts, care must be taken to use the right anisotropic material parameters and a suitable modeling method for the reinforcing layers. In the process, the approach taken to simulating locally applied fiber strands in 3-D winding differs in various aspects from that used for semi-finished fiber parts applied over a surface area such as woven or non-crimp fabrics.

FIGURE 1 Prototype of the roof frame, implemented using AdditiveCarbon (© Cikoni)

FIGURE 2 Reference assembly under consideration with roof frame left and right (© Audi)

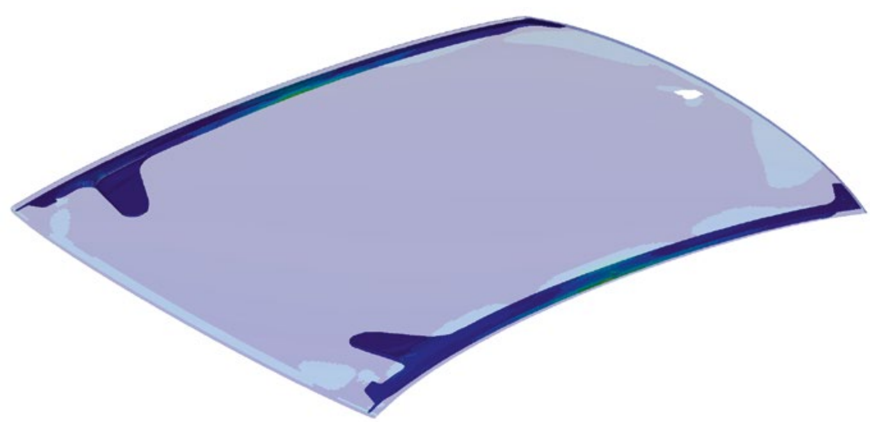

FIGURE 3 FEM model of the reference assembly as the starting point for component sizing (© Audi)

Degrees of Freedom and Boundary Conditions

The actual design task involves optimally exploiting the volume for additive manufacturing and designing the base body of the components in accordance with the process-specific boundary conditions. Here, scope exists to capitalize on the advantages of additive manufacturing, as undercuts and openings can be implemented with fewer restrictions. In addition to a supporting function, the base body should also assist guidance and the exact positioning of the carbon fiber strands. The winding base in the direction of the fibers should always have a convex form to prevent fibers running freely through the space and thus ensure that the mechanical potential of the fibers is exploited, as otherwise resilience under pressure and bending loads would be reduced.

From a mechanical perspective, the base body acts like a sandwich core, significantly boosting flexural stiffness with increasing construction height. For this purpose, the core must possess sufficient inherent rigidity, which was achieved by integrating ribs, despite the low wall thickness overall. At the same time, ancillary elements for the 3-D winding process, reversal points and inserts for subsequent connection to neighboring parts can all be integrated. The path of the guide elements must be designed in such a way that it follows the natural placement path of spatially wound fibers, as otherwise the fiber strands cannot lie undisturbed on the base body, which would, in turn, entail mechanical drawbacks. Geodesic paths need to be plotted for this, Figure 4 (top).

Further boundary conditions need to be taken into consideration in the design that differ from the design process of a classic FRP component with surface reinforcement. For example, the 3-D winding paths should be planned so as to ensure the carbon fiber roving can be placed continuously wherever possible, as any break would constitute a weak point for the component. In addition, a way of designing intersection points and the associated varying thicknesses as technically unavoidable elements of the process needs to be defined.

Significantly differing levels of stiffness and strength in the materials used for the base body and reinforcement underlines the need for the load application point to be always located directly in the carbon fiber. This can be achieved, for example, by laying loops, Figure 5. Otherwise, a significant portion of the carbon reinforcement potential remains unused. The design of the additively manufactured component for the roof frame under consideration following these assumptions can be seen in Figure 4 (bottom).

From a mechanical perspective, the base body acts like a sandwich core.

Implementing Functional Prototypes

To create prototypes, several printed base bodies made from polyamide (PA)-12 were produced using Selective Laser Sintering (SLS) and prepared for the subsequent winding process, Figure 1 and Figure 5. This was not performed automatically for the concept study, although the component design was already performed with scope to fully automate the winding process in mind. Apart from the duration of production, there were no disadvantages arising from manual production owing to the designed-in precise guidance for the fiber strands on the additively manufactured component.

Pre-impregnated fibers – so-called towpregs – with a curing and space-filling epoxy resin system were used to ensure constant quality and consistent volume content. Thanks to the use of such towpregs and an almost fully convex winding surface, consolidation during curing was not absolutely essential for the mechanical characteristics. However, tests performed indicate scope to achieve a more even surface finish through consolidation using a vacuum sack or an elastic, reusable membrane, where this is considered necessary for the intended purpose.

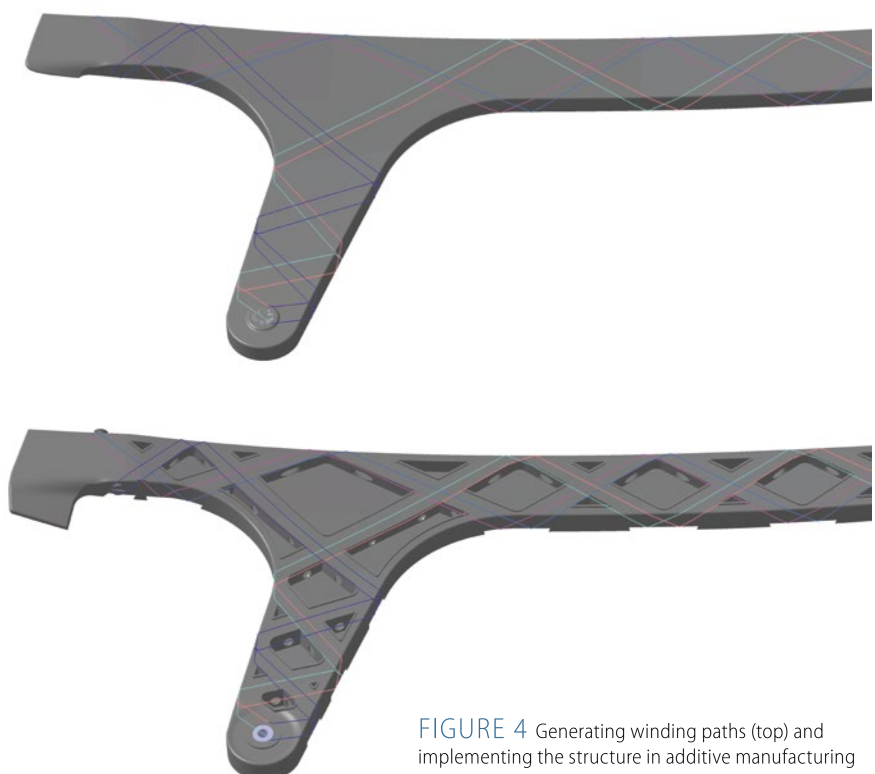

FIGURE 4 Generating winding paths (top) and implementing the structure in additive manufacturing (bottom) (© Cikoni)

FIGURE 5 Detailed view of the load application point integrated through winding (© Cikoni)

Conclusion and Outlook

The successful outcome achieved during the concept study between Audi and Cikoni to produce a lightweight roof frame using the AdditiveCarbon process were impressive in terms of quality as well as the required manufacturing tolerances. The final component weight meets the goals and differs by only a few grams from the overall weight estimated in the design model.

The optimum design of a component produced using this method differs considerably from other processes. The methodological insights gained for this purpose are to be used in future for other suitable components in the vehicle body structure to identify additional potential for the process. The intention is to address, among other things, the questions of a fully automated process, from additive manufacturing to the completely wound, three-dimensional component and a partly automated run based on a modular and rule-based design methodology.

From a holistic perspective, feasibility studies are also being conducted to identify suitable components, unit volume scenarios, and material combinations from a commercial perspective. Here, variants with lost cores and the use of natural fibers to improve the aspect of sustainability may represent interesting process alternatives.

> The design of a component thus produced differs considerably from other processes.