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Design and automated manufacturing of profiled composite driveshafts

Abstract: The high specific strength and stiffness characteristics of composite materials such as carbon fiber-reinforced plastic (CFRP) allow a significant weight reduction of the structural machine components such as automobile driveshafts. But high material cost and rather low productivity of the established manufacturing processes (e.g., filament winding) often inhibit the use of CFRP components in a high-volume car series. In this paper, a novel composite driveshaft system based on a profiled CFRP tube is presented. This system is designed to be produced by a continuous pultrusion process to achieve a significant reduction of the manufacturing costs. A cost assessment study was conducted to quantify the benefit of the developed continuous manufacturing process. In comparison with the state-of-the-art filament winding process, a cost reduction of 36% for the composite shaft body can be obtained. Moreover, the proposed fiber layup processes – braiding and continuous winding – offer the potential to manipulate the reinforcement architecture to maximize material utilization without reducing the manufacturing efficiency. This potential is investigated and validated by experimental tests. A difference in the load bearing capacity of more than 100% between different reinforcing architectures is shown.

Keywords: braiding; composite driveshaft; continuous manufacturing; profiled cross-section; textile pattern.

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1 Introduction

The international competition and political guidelines regarding a significant reduction in greenhouse gas emission demand a raise of energy efficiency in machine manufacturing and operation [1, 2]. Especially in the field of mobility systems, lightweight designs utilizing carbon fiber-reinforced plastics (CFRP) are used more and more to lower the mass and energy consumption of airplanes, automobiles and ships. Aside from the outstanding mechanical performance of CFRPs, functional benefits such as high corrosion resistance and high internal damping coefficients are further reasons for the increasing use of those high-technology materials. The realization of lightweight solutions for rotating components within power trains of mobility systems is of particular importance, because here the mass as well as the mass moment of inertia can be reduced.

To reach a high lightweight design level, the extremely high strength and stiffness in fiber parallel direction has to be utilized while the much lower mechanical performance perpendicular to the fiber direction has to be respected. This can usually be achieved better in primarily one- or two-dimensionally loaded parts such as driveshaft bodies compared to complexly loaded components (e.g., load introduction elements), which often remain metallic. This general design is depicted in Figure 1.

In this context, driveshafts were among the first automobile components that were chosen for an industrial use of CFRPs in the 1980s [3]. Until now, no standard design could be established in the automotive industry. One major reason is seen in the very high cost of composite structural parts that can exceed the cost of a standard steel part in this industry by 600%–800% [4].

These high costs of CFRP components are influenced by several factors. One factor is the price of carbon fibers, which is usually higher than the price of commonly used steel alloys. Another main factor are the process costs including the labor costs resulting from manual and discontinuous processes such as filament winding, which is a standard process for the manufacturing of composite driveshaft bodies [1, 3]. While filament winding is a well-established

Figure 1 General design of a composite metal hybrid driveshaft.

automated process for the manufacturing of composite hollow structures, it exhibits a rather low productivity, since usually only five rovings or less are laid down in parallel.

Further costs arise from the joining of the metallic load introduction elements and the CFRP shaft body. In many cases, the state-of-the-art joining technologies such as bolting, adhesive bonding and press fit connections [5] are used. Bolting requires precise machining steps, additional connection elements and securing. Adhesive bonding usually gives high requirements for the surface treatment and quality control. Press fit connection types require narrow tolerances, usually requiring straightening process. These additional process steps increase the cycle time and component costs.

Finally, as composites are still a new engineering material compared to the classic metallic materials, only few dimensioning and design rules as well as standardized machine elements exist. Thus, the development time for new composite lightweight products increases, adding to the high component cost.

In this context, a novel design for the CFRP driveshafts was developed at the Institute of Lightweight Engineering and Polymer Technology (ILK) of the Technische Universität Dresden (TUD). It is based on a profiled driveshaft body, which offers the possibility of continuous manufacturing and efficient assembly processes [6–8]. This so-called “smoothed spline (SSP)” joint offers a high load introduction capability via a form fit requiring no additional assembly processes such as milling and bolting. The fiber-adapted spline joint cross-section is already formed during the manufacturing process [9]. This generic design can be easily adapted to different applications facilitating the standardization of composite driveshaft components and the introduction of a model kit based on semifinished driveshaft bodies, aiming at a reduction of the development time and cost.

After presenting the design and the specific mechanical behavior of the developed driveshaft system, this paper focuses on the manufacturing process. Unlike the aforementioned discontinuous filament winding process, the proposed manufacturing process works in a highly productive, continuous fashion. The preform is provided on a mandrel with a constant feed. Hence, a novel preforming process is needed to form the profiled cross-section of the

shaft body. In this paper, the serial manufacturing concepts as well as prototypically manufactured demonstrator parts are presented. The cost savings potential of this manufacturing approach is investigated by a cost assessment study based on an exemplary automotive application, comparing the discontinuous filament winding process with the novel pultrusion concept.

The fiber layup processes – braiding and continuous winding – allow a precise manipulation of the reinforcement architecture in terms of fiber orientation but also regarding the textile pattern. This opens up new design parameters during the manufacturing of the driveshaft body. For example, the layer stiffness can be modified with the aim of achieving an even stress distribution in the driveshaft laminate subjected to shear loads, for which a concept is presented. To enable an application of those concepts, the strength and stiffness parameters of different braided and wound patterns are experimentally investigated.

2 Design of profiled driveshafts

A modular system concept for lightweight driveshafts has been developed at the ILK to reduce the development time and cost. This system consists of a composite shaft body with its profiled cross-section (Figure 2B) and a broad range of functional components such as flanges, gear wheels, universal joints or bearings, which can be chosen from a standardized catalogue. A customized power train component is manufactured by cutting the composite shaft body to length and a subsequent assembling of the functional components at the required positions (see Figure 2A–C) [6, 7]. Here, the profiled cross-section allows an easy assembly by a form fit connection.

Although this design is highly flexible and permits the manufacturing of potentially cost-efficient semifinished products, the undulated laminate cross-section reduces the load bearing capacity of the driveshaft when compared to a shaft with cylindrical cross-section. Therefore, in a further work, this modular concept has been adapted to meet the requirements of high-performance applications.

Figure 2 Concept for a modular driveshaft system with a profiled shaft body: complex drivetrain (A), linearly extruded shaft body (B), and demonstrator part (C).

2.1 Driveshaft concept

The newly developed driveshaft concept focuses on the provision of high-performance semifinished driveshaft bodies, which are equipped with metallic end fittings for concentrated load introduction (Figure 3, top). A basic geometry as depicted in Figure 3 is chosen. It features a profiled inner laminate, the so-called profiled shell (1), for load introduction, supplemented by axial reinforcements (2) and enclosed by a cylindrical laminate, or cylindrical shell (3). This cylindrical shell efficiently transmits loads over the span of the driveshaft, enhancing the performance of the component when compared with the previous design (Figure 2). This novel design recently was successfully patented [10].

In order to maintain the advantage of a continuous manufacturing process, the profile is linearly extruded to constitute the shaft body. Thus, the profiled geometry not only influences the load introduction capabilities but also the mechanical performance of the shaft in the “undisturbed” area between the load introduction zones. Those two features have to be matched in order to develop a viable design. For this, a simulation model was created and a parameter study on favorable geometrical parameters of the profiled cross-section was conducted [11]. Now, the influence of the textile configuration of the shaft laminate is investigated.

2.2 Stress distribution and opportunities of improvements

The mechanical performance of the developed driveshaft is not only dependent on the chosen cross-section geometry but also on the configuration of the driveshaft laminate. For tubular driveshafts, the shear strain is linearly dependent on the torsional angle and radius (Figure 4,

Figure 3 Novel driveshaft concept with modified cross-section consisting of a profiled shell (1), axial reinforcements (2), and cylindrical shell (3).

left). Hence, the shear stress distribution equals the strain distribution scaled with a stiffness coefficient as long as no yield effects are prevalent. Therefore, the tubular driveshafts with ideal elastic material behavior and constant stiffness properties will fail at the outer surface of the tube while subjected to a torque load (as shown in Figure 4A).

Here, the composites offer new opportunities to equalize the material effort over thickness by adapting the stiffness properties of the material to the radial coordinate. Using the step-by-step buildup at the manufacturing process, a gradual layup can be realized. In the most potent lightweight design, the stresses at every layer will cause the same material effort. To approach this ideal design, different strategies can be used. Reinforcing materials with different stiffness values such as glass and carbon fibers can be used, as known from tension loops [12]. Moreover, the adjustment of fiber orientation is a common strategy [13].

Another strategy to adapt the stiffness of the layers is the adjustment of textile parameters during fiber placement with a braiding machine. This is achieved by modifying the yarn carrier setup (see Section 4). By altering the level of interweaves within the layer, the mechanical material properties can be adjusted. This effect is investigated experimentally using a CFRP tubular specimen to determine the mechanical properties of the laminate.

3 Continuous manufacturing process

For the investigated driveshaft concept, a continuous manufacturing process is focused. For composite profiles and tube bodies, the pultrusion process as depicted in Figure 5 is well established in the industry [14–16].

Figure 4 Stress distribution in shafts under torque loading for constant material stiffness properties (A) and for a designed anisotropic material (B).

Figure 5 Basic pultrusion process.

In this process, composite parts can be manufactured in large quantities. The laminate layup of those products usually contains primarily fibers oriented in axial direction in order to bear the pulling forces during manufacturing. This leads to parts with a high axial stiffness and strength, while a high resistance for shear stresses cannot be expected. For torque loads leading to shear stresses, an off-axis reinforcement (e.g., $\pm 45^\circ$ orientation) is needed. For this, no continuous industrial process is known, so a concept is elaborated and presented in this paper. In this concept, established laydown processes are combined with the state-of-the-art infusion processes to form a production arrangement. This arrangement also contains a novel device for the continuous preforming of the profiled geometry, which is validated experimentally on a laboratory scale.

3.1 Serial manufacturing concept

By eliminating the manual process steps and utilizing the highly productive and automated preforming processes such as braiding or continuous winding (Figure 6), a significant reduction of part cost combined with an enhancement of the reproducibility of the manufacturing results is aspired. Figure 7 depicts one of the currently two braiding machines in service at the ILK. This so-called axial braider features yarn carriers oriented in parallel to the mandrel axis. It provides 72 carriers on the outer track and 48 carriers on the inner track (Type: KFh 1/72/48-100). The second braider is a 288-carrier radial braiding machine, where the carriers are oriented perpendicular to the mandrel axis (Type: RF/288-100). Aside from some minor effects on fiber tension and braid compression, the two braiding machine designs feature comparable characteristics. Both braiding machines were manufactured by HERZOG Flechtmaschinen GmbH, Oldenburg, Germany. The axial braider was chosen for depiction due to its smaller dimensions.

Dependent on the carrier setup, braiding machines allow a variation in the textile pattern up to the creation of unidirectionally oriented layers without interweaves.

Figure 6 Process principle with resulting reinforcement types: (A) continuous winding and (B) braiding.

Figure 7 Axial braiding wheel with two carrier tracks.

Extensive modifications of the 288-carrier braiding machine permit an additional variety of the possible braiding patterns.

The choice of those patterns influences the part performance, since the resulting reinforcement architectures differ in their characteristics. Unidirectional reinforcement (Figure 6A) leads to very high mechanical properties. This can be attributed to a low level of fiber undulation.

Bidirectional reinforcement obtained by braiding usually exhibits a textile binding with fiber undulation and interlocking of fibers (Figure 6B). By increasing the number of weave points, the fiber undulation in the reinforcement layer increases. This leads to a significant

decrease in stiffness and strength properties but an increase in the elongation at break and damage tolerance [17, 18]. This allows for a modification of mechanical layer characteristics without a negative impact on the productivity of the continuous process, since no adjustment of braiding speed was necessary when modifying the braiding pattern (compare section 4.1). Unidirectional winding, on the contrary, would allow for a faster manufacturing speed, since the bobbins merely rotate around the mandrel instead of following a more complex path with intersections as it is the case in the braiding process. However, as the expected pultrusion speed (0.8–1 m/s) is limited by the injection process, this potential increase in layup rate cannot be utilized. If a significant increase in the injection and consolidation speeds can be achieved, the layup process will have to be reevaluated and the productivity could be enhanced further.

The general concept for serial manufacturing feasible for both preforming processes is depicted in Figure 8:

- Preforming of the profiled laminate on continuously fed mandrels;
- Forming of the profile;
- Supply of the axial reinforcement;
- Preforming of the cylindrical outer laminate;
- Infiltration in a pultrusion nozzle and
- Consolidation, straightening and pull-off.

One of the main challenges is the reproducible forming of the profiled laminate. For this task, a preforming device was developed. With the successful testing of the continuous preforming, the elaborated serial manufacturing process is validated [11]. Figure 9 shows a selection of profiled shaft geometries and sizes, which were prototypically manufactured.

3.2 Cost assessment study

A preliminary cost assessment study has been conducted on the novel driveshaft design and the related continuous pultrusion process to compare the manufacturing costs with those of a conventional driveshaft body produced by a wet-winding technology. Both driveshafts have to fulfill the same requirements, derived from an exemplary automotive driveshaft. The calculation is based on a job order production by a manufacturer specialized in the respective processes. The assumed production scenario and shaft dimensions are summarized in Table 1. This study focuses on the composite manufacturing processes and the costs for metallic load introductions and the assembly processes involved were not yet considered.

The costs are determined by an overhead calculation considering the following direct costs: material cost, labor costs, machine costs, and tool costs [19]. The assumed values for determining the direct costs per driveshaft are specified in Table 2.

The design of the new profiled lightweight shaft bodies is predestined for manufacturing by a combined braiding-pultrusion process. The pultrusion facility (Figure 10) consists of a mandrel feeding station, braiding wheels for the profiled shell, a preforming station for the axial fibers, and continuous winding machines as well as a braiding wheel for the cylindrical shell. The impregnation and consolidation of the preforms is conducted in a pultrusion die. Following the die, which consists of an impregnation unit as well as a heating and a straightening zone, a caterpillar pull-off unit is pulling off the hollow profile still containing the mandrel. Afterward, a parallel moving saw cuts the consolidated shafts between the mandrels. The mandrel length corresponds to the required shaft length, so the cutoff can be kept to a minimum. Directly after the

Figure 8 Process principle for a continuous pultrusion of profiled driveshaft bodies.

Figure 9 Different prototypic profiled shaft shapes.

Table 1 General shaft parameters.

Produced shafts per year	500.000 pcs.
Period of production	8 years
Outer diameter	70 mm
Length	1370 mm

Table 2 General calculation parameters.

Amortization period	40.000 h
Energy costs	0.22 €/kWh
Rent including heating	15 €/(m ² ×mo.)
Hourly wage rate	100 €/h
Overhead rate	10%

Table 3 General pultrusion facility configuration and component costs for the calculation of machine costs.

Number of needed pultrusion facilities for yearly production		3 pcs.
Facility component	Component count/facility	Component cost [€/pc.]
Mandrel feeding station	1	15,000
Braiding wheel	3	360,000
Preforming station	1	7000
Compression winder	1	10,000
Continuous winder	11	150,000
Pultrusion die	1	50,000
Caterpillar takeoff unit	1	25,000
Cutter	1	20,000
Tempering furnace	1	40,000
Mandrel pull-off device	1	8000

Table 4 Necessary tool costs per pultrusion facility – all components are assumed to be replaced one time during manufacturing time.

Component	Component count/facility	Component cost [€/pc.]
Pultrusion mandrel	70	
Preforming tool	2	10,000
Pultrusion tool	2	20,000

rough cut, the mandrel is removed and the shaft is cut precisely to the defined length. The primary parameters considered for the cost estimation of the novel continuous manufacturing process are summarized in Tables 3 and 4.

The unit costs of a profiled shaft body manufactured by the combined braiding-pultrusion process are compared to an equivalent driveshaft body produced by wet winding. The assumed winding process is shown in Figure 11, where five driveshaft bodies are simultaneously wound using only one winding machine. After the finishing of the winding process, the impregnated tube preforms including the mandrels are taken to a curing oven

with rotating jaw chucks for the hardening of the resin. In parallel, the next charge is wound. After curing, the mandrels are removed and prepared for the next use, while shafts are cut to length. The assumed costs of the winding machines as well as other process components are summarized in Tables 5 and 6.

Due to the differences in geometry and manufacturing restrictions, the layout for the two shaft types differs. First, the profiled shaped inner layers of the profiled shaft have no round shape. Thus, the bearing strength of the profiled $\pm 45^\circ$ layers for torsional load is decreased

Figure 10 Schematic diagram of the assumed pultrusion facility for cost calculation.

Figure 11 Schematic diagram of the assumed winding machine for cost calculation.

Table 5 Configuration of winding machine and associated facilities for the calculation of machine costs.

Number of needed winding machines for yearly production		25 pcs.
Facility component	Component count/facility	Component cost [€/pc.]
Winding machine	1	500,000
Mandrel pull-off device	1	15,000
Curing die	1	8000

Table 6 Necessary tool costs per winding machine — all components are assumed to be replaced one time during manufacturing time.

Component	Component count/facility	Component cost [€/pc.]
Winding mandrel	22	800

compared to the cylindrical layers. This has to be compensated by a higher thickness of layers. Second, the achievable fiber orientations are limited by the winding process due to the placement of the rovings on the mandrel. A minimum placement angle of $\pm 15^\circ$ was assumed, which still allows a high productivity. This limitation results in a decrease of the bending stiffness of the driveshaft body, which also has to be compensated by a higher layer thickness for the axial oriented layers of the wound shaft body. The resulting layups, as shown in Table 7, fulfill the same requirements concerning the stiffness and strength. For a better comparability, the profiled shaft cross-section is converted to a constant wall thickness with a circular

Table 7 Layup of the different shaft concepts (an outer diameter of 70 mm).

	Reference wound shaft	Profiled shaft
Wall thickness $\pm 45^\circ$ layers	2.0 mm	2.1 mm
Wall thickness axial layers	3.8 mm	2.3 mm
Fiber angle axial layers	15°	0°

cross-section. The used materials and their costs are specified in Table 8.

3.3 Results

In Figure 12, the results of the preliminary cost assessment study are depicted. The tool costs equal only approximately 0.1% of the overall costs and are not included.

As shown in the preceding diagram, the manufacturing costs of the profiled driveshaft bodies are approximately 36% lower compared to the filament wound shafts. The material cost has the highest influence on the resulting part cost followed by the labor cost. Both are lower for the pultruded profiled driveshafts due to the high orientation of the axial fibers, which can usually not be achieved with a winding process, and the high level of automation of the pultrusion process. The costs for tools

Table 8 Used materials and estimated material costs.

	Material type	Cost [€/kg]
Fibers for $\pm 45^\circ$ layers	Torayca T300	17
Fibers for axial layers	Torayca M35J	80
Matrix	Epoxy resin	8

Figure 12 Summarized cost calculation results for reference cylindrical and profiled shaft body.

and machines show no significant impact on the overall composite part cost.

An additional positive effect of the continuous process is the high flexibility for manufacturing individual driveshafts if different component lengths are requested. For the filament winding process, the length of driveshafts is restricted by the size of the winding machine, whereas the continuous pultrusion process shows virtually no limitation in length.

4 Mechanical properties of composite driveshaft bodies

Two extensive experimental studies have been made to investigate the mechanical properties of the novel driveshaft design. In a first study, the influence of the cross-sectional geometry on the load bearing capacity was determined. The ultimate strength as well as the failure modes of driveshafts under torsional loading with different cross-sectional shapes were experimentally determined and compared to the results of numerical simulations. The calculated failure loads as well as the failure modes were almost the same compared to the experimental results [18].

The aim of the second experimental study was the determination of the influence of different braiding patterns on the torsional stiffness and strength of the novel driveshafts. The novel modification of the braid pattern enables an adapted undulation level, which has a great influence on the strength and stiffness in textile structures. In the newly developed continuous manufacturing process, the braid modification can be utilized in each

separate layer. The results of this second experimental study are presented below.

4.1 Modifications of braid patterns

The braiding machines were modified to enable the fabrication of textile preforms with less undulation of the reinforcing fibers. Figure 13 shows the pictures of exemplary tube preform textures and the corresponding textile models generated by the software TexGen 3.5.2 (by University of Nottingham, UK). The pattern on the left, the classic diamond braid, exhibits the highest degree of interweaves, while, on the right, a unidirectional reinforcement with no interweaves can also be implemented in the manufacturing process. The modified braid patterns in between represent the medium levels of interweaves. The torque specimens with all these textile patterns were manufactured on the braiding machine and tested to determine the influence of the textile structure on the mechanical properties such as torsion stiffness.

4.2 Specimen manufacturing and testing

The 288-carrier braiding machine was used to manufacture torsional tubes with an outer diameter of 20 mm and an inner diameter of 12 mm. The fibers used were supplied by TohoTenax Europe GmbH, Wuppertal, Germany (Type: Tenax®-E IMS65 E23 24K 830tex). They are braided on a stiff core, which is guided by a handling robot to guarantee the accurate speed necessary for the braiding angle of 45°. Figure 14 shows two exemplary placement processes. Those

Figure 13 Different investigated braid pattern types.

preforms were infused in a Resin-Transfer-Molding-(RTM-) Process using the Resin Araldite® LY556 with Aradur® 917 hardener. Both chemicals were supplied by Huntsman Advanced Materials GmbH, Bad Säckingen, Germany.

The manufactured specimens are subjected to torque loading using a tension-torsion testing machine “Z250/SN5A” with an ultimate torque capacity of 2000 Nm. This machine was manufactured by Zwick GmbH & Co, Ulm, Germany. The test is performed under compensation of axial loads with an application of torque at a twist speed of 5°/min (quasi-static). Figure 15 provides an overview of the specimen geometry and the fixture used to introduce the torque loads.

Further experiments are in preparation to assess the influence of specimen geometry. For those tests, the manufacturing of specimen with an outer diameter of 100 mm and a wall thickness of 18 mm is planned. For testing those tubular samples, a servohydraulic test stand with an ultimate load capacity of 40 kNm is available at the ILK.

4.3 Test results

Figures 16 and 17 show the achieved failure load levels and stiffness values of the tubular specimens depending

Figure 14 Two braiding placement processes with different textile patterns.

Figure 15 Torque specimen geometry (left) and testing setup (right).

Figure 16 Torsional strength of specimens with different textile patterns.

Figure 17 Torsional stiffness of specimens with different textile patterns.

on the textile structure (compare Figure 13). The test results mainly reflect the influence of the textile structure, because all tested driveshaft specimen had the same geometry (an outer diameter of 20 mm and an inner diameter of 12 mm). Nevertheless, the results obtained are geometry dependent and should not be used as characteristic material properties.

Based on the standard diamond braid with a high undulation of the fibers, the modification of the braids leads to an improvement in the load bearing capacity of up to 39% and up to 16% in torsion stiffness. When the textile pattern is transformed into a unidirectional layup, the raise in the mechanical properties reaches 104% (ultimate torque) and 22% (torsion stiffness).

These different material properties can be used to adjust the material properties on the number of layers according to the requirements and to increase the total

capacity of the driveshafts, wherein the production rate is not negatively affected by the improved braiding.

5 Conclusion

High manufacturing costs often limit the application of lightweight structures made of CFRP. Therefore, new design concepts and related large-scale production technologies for CFRP components have to be developed. In this paper, a novel approach to design and manufacture high-performance composite driveshafts is presented. The basic concept is based on a profiled CFRP shaft cross-section to join the metallic load introduction elements easily by a positive connection without any additional joining processes. Besides mechanical performance, this connection type is designed for a highly automated, continuous manufacturing in the pultrusion process.

The successful application of the novel driveshafts requires reproducible and economic manufacturing processes. Hence, an innovative process chain from continuous preforming to consolidation has been developed and partly validated on the machinery equipment of the ILK. Based on this experience, a cost assessment study was conducted to compare the manufacturing costs of the profiled driveshaft with the state-of-the-art shafts. A cost savings potential of approximately 36% was identified, emphasizing the economic advantages of continuous manufacturing.

In this paper, an approach to equalize the load distribution in the torsional layers of driveshafts is presented, with the aim of using the material to full capability. The concept developed here is based on the characteristics of adapted braid patterns. Extensive investigations were conducted on torsional loaded cylindrical specimens to characterize different patterns. The load bearing capacity and torsional stiffness of the braided structures can be significantly increased by 39% and 16%, respectively, while maintaining the highly productive braiding process as preforming technology. When the textile structure is transformed into a unidirectional layup, a raise in the mechanical properties of 104% (ultimate torque) and 22% (torsion stiffness) can be achieved.

In summary, the profiled driveshaft concept and the associate continuous manufacturing process allow the high productive fabrication of high-performance lightweight composite driveshafts. The economic manufacturing opens up opportunities for further establishment of carbon components in mobility systems as well as in the general industry.

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