

The greatest challenge for lightweight construction with fiber reinforced polymers today is the development of mass production capable – that is fast and cost effective – manufacturing techniques for large area components such as doors, roof modules or tailgates as well as structural components such as B pillars, sills or underbodies with the required mechanical performance (figures except Fig. 4: BASF)

Materials for the Future of Lightweight Construction



Composites. Continuous fiber reinforced composites allow the automotive industry to achieve weight savings that were previously not possible. In combination with different matrix polymers as well as various types of fiber and fabric architecture they also offer a high level of design freedom for component parts. At the same time cost efficient processes that are suitable for mass production are the prerequisite for market success.

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Lightweight construction is not a new concept; indeed it is a well established strategy in vehicle construction (Title picture). New momentum has however come on the one hand from the intensive efforts being put into alternative drive systems, particularly electric cars, but on the other also from conventional vehicles that will dominate Europe's roads for decades, where lightweight construction is vitally important since every kilo counts: From 2020 the European Union will require every European vehicle manufacturer to achieve an average fleet emission level of 95 g CO₂/km. For comparison the actual value achieved in November 2011 was still

around 143 g CO₂/km. This means a reduction of around a third in just under a decade. Exceeding this value will lead to large fines for the automotive industry. Alongside optimized traditional and alternative drives as well as improved rolling and air resistance lightweight construction is a lever in meeting the reduction targets: Every 100 kg of weight saved means 0.4 l less fuel consumption per 100 km traveled or around 10 g less carbon dioxide emissions.

Following the large scale uptake of short glass fiber reinforced polymers for lightweight construction and the acceptance of the advantages of long glass fiber reinforced material by the market the automotive industry now has to face the next challenge: continuous fiber reinforced composites for mass production. The ambitious weight and associated fuel consumption reductions of the next generation of vehicles can be achieved

with these material and component types.

Short, Long and Continuous Reinforcement

Short Glass Fiber Reinforcement: Since the beginning of the 70s when the first mass produced polyamide (PA) air intake from Dr. Ing. h.c. F. Porsche AG, Stuttgart, Germany, saw the light of day, short glass

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fiber reinforced polymers such as PA and polyurethane (PUR), as well as polyethylene (PE) and polypropylene (PP) have continuously advanced automotive lightweight construction in demanding applications. They will also continue to advance it on a broader and more global scale through the proliferation of innovative components. Amongst the most interesting examples of the past few years is the replacement of metals by engineering thermoplastics in engine mounts, stabilizers and transmission cross beams. However, ten years ago it was also not possible to produce bumper supports made from polyamide or front ends, B pillar inserts or oil and seat pans in polymeric materials.

Success was not only made possible by the continuous development of the matrix polymers, but also by the increasing ability to predict the behavior of polymer parts under loading using computers, e.g. advanced simulation tools such as Ultrasim from BASF SE, Ludwigshafen, Germany. Furthermore, these material developments are not over yet: Polyamides such as the now even stiffer Ultramid Endure grades, which have continuous service temperatures of up to 220°C for components near to turbo charge engines, or even more customizable crash optimized PA6 grades such as Ultramid B3ZG10 CR show that a great deal of potential within short glass fiber reinforced materials remains to be unlocked. In addition there are alternative raw materials with new combinations



Fig. 1. The bodywork of the Artega GT, a low volume sports car made in Delbrück, Germany, consists mainly of polyurethane reinforced with short mineral and carbon fibers

of properties such as for example Ultramid Balance (PA610) with high chemical and hydrolysis resistance.

In the case of polyurethanes PUR-RRIM technology has been further developed and in 2009 had its most spectacular success with the world's first all PUR mass produced vehicle body shell (Fig. 1). The in part large area bodywork components of the low volume Artega GT sports car from Artega Automobile GmbH, Delbrück, Germany, were produced using RRIM (Reinforced Reaction Injection Molding). In this process the PUR base components which contain short glass fibers are mixed at high pressure in a mixing head. After this the low viscosity reaction mixture is injected into the closed tool within 1 s and just 30 s later the fin-

ished part is demolded. Elastolit grades R8, R8HT, K4 and D from BASF Polyurethanes GmbH, Lemförde, Germany, were used for the Artega GT and individually optimized for the requirements of the door skins, wings, bumpers, tailgate and roof frame. Particularly for low volume mounted parts that require low cost tooling, PUR systems can prevail despite competition from metal or thermoplastics. In this case the very good flow properties stemming from the processing of liquid components and low internal mold pressures are a clear advantage. Stiffness, dimensional stability, toughness and low thermal expansion are some of the benefits of the material. PUR bodywork led to a weight saving of around 40 % for the Artega GT.

Long Glass Fiber Reinforcement: At the same time however a trend towards long glass fiber reinforced polymers can be seen for special applications and requirements. BASF has therefore been marketing Ultramid Structure since 2010. This material was chosen in 2011 for the wheel of the smart forvision concept car (Fig. 2). What is special about this long glass fiber reinforced (LGF) polyamide is that during the injection molding process a three dimensional fiber network of about 3 to 6 mm long fibers is created which acts as a skeleton for the component, as can be seen here with the example of an internally developed crash absorber (Fig. 3, center). This skeleton structure ensures very good mechanical properties: creep behavior, warpage and energy absorption are similar to metal without losing the traditional advantages of a thermoplastic. In or →



Fig. 2. The new smart forvision concept car presented at the IAA 2011 was equipped with the world's first thermoplastic wheels that have the potential to be mass produced. They are made from long glass fiber reinforced polyamide and with a weight of 6 kg they are some 30 % lighter than mass produced aluminum wheels reducing the overall weight of the vehicle by 12 kg

der to give a complete description of the (failure) behavior of components made from LGF polyamide BASF has once again expanded its simulation tool: The precise failure during a collision with the Ultramid Structure crash absorber can be predicted using Ultrasim (Fig. 3, bottom).

Long glass fiber reinforced composite materials made from polyurethane foam when combined with thermoplastic film offer options for the roof module as well as other mounted parts of commercial vehicles such as radiator grills (Fig. 4). This is an application area for Elastoflex E from BASF Polyurethanes. In the roof module of the smart fortwo a thermoformed multilayer film is long-fiber injection (LFI) back foamed with a long glass fiber reinforced polyurethane. What is important here alongside the individually adjustable level of stiffness and strength is the low and isotropic thermal expansion of the PUR system.

Continuous Fiber Composites: For all of these short or long fiber reinforced vehicle components the weight saving per component compared to metal is between 30 and 50 %. These already allow high stiffnesses and strengths to be achieved. The future of lightweight construction, particularly for the bodywork and the chassis, however lies in continuous fiber reinforced components. In respect of finished component properties and process technology, Continuous Fiber Reinforcement (CFR), goes a fundamental step further. It will therefore lead to a further increase in the proportion of polymer in vehicles. In the case of thermoplastic processing, injection molding or compression processes are combined with localized continuous

fiber reinforcement, thereby allowing a significant increase in strength, stiffness and energy absorption (Fig. 5).

One option is conventional injection molding which uses light continuous fiber inserts for local reinforcement of components. These are unidirectional thermoplastic impregnated rovings (UD tapes) or fabric reinforced prepregs called thermoplastic laminates. Whilst thermoplastic laminates (or organo sheets) are particularly suitable for large area hybrid parts, UD tapes are advantageous for local reinforcement. With their help component properties can be very effectively optimized through the nearly limitless choice of layer construction and its associated fiber orientation. In both cases the prepregs are thermoformed to three dimensional shapes, after this they are injection overmolded for example with a glass fiber reinforced polyamide and thus made into hybrid components with high stiffness and strength. A seat back developed jointly by BASF and Faurecia is close to mass production (Fig. 6). This process is however also in principle suitable for other structural components such as the B pillar or the sills (see Title picture). As in a pure injection molding application the first step in the development process with continuous fiber reinforcement is establishing the ability to simulate the component behavior including crash performance. Based on component tests CAE material models of the overmolded continuous fiber structures were developed.

In terms of process technology overmolding of the pre-formed laminate fiber structure offers all the advantages of thermoplastic injection molding, such as short cycle times, high levels of automa-



Fig. 3. Long glass fiber reinforced polymers form a three dimensional glass fiber network during injection molding (center of picture), which gives the component its exceptional mechanical performance for instance as a bodywork crash absorber. The behavior of such demanding components can now also be calculated and predicted via computer simulations

tion, reproducibility, modularity, functional integration as well as recyclability. Thermoplastic laminates utilize their strengths as 2-D components: They are used as semi finished products and are thermally formable either during or shortly before the overmolding step.

An additional novel technology is currently being developed for components which are manufactured by injection molding with steel cord reinforcement (EASI technology). Access to structural applications is possible through the joint development partners Bekaert, Kortrijk/Belgium, and voestalpine Plastics Solutions, Putte & Roosendaal/the Netherlands. By using polyamide as the injection molding material the components can be cathodic dipped and so are suitable as mounted parts as well as for use in unfinished bodywork (BIW: body in white). These components combine the necessary performance for structural requirements such as strength and stiffness with the ductility of highly resilient materials so that in a crash extremely high energy absorption and structural integrity are guaranteed.

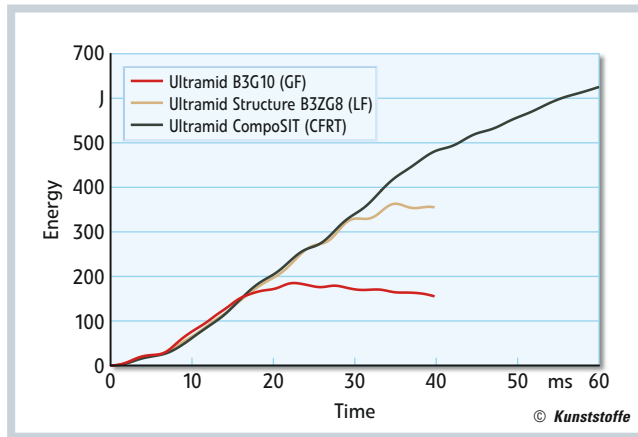
BASF is available as a development partner for the automotive industry for all these thermoplastic reinforcement technologies.

Fig. 4. Long fiber reinforced polyurethane is already being used for the MAN radiator grills
(photo: MAN-Truck)



new materials is resin transfer molding (RTM) with the help of which large and complex composite components are created in a resin injection, press and mold process. In doing so, after being placed in a temperature controlled mold which is subsequently closed, dry multilayer fiber or textile structures are impregnated with a very low viscosity polymer resin. Due to their low starting viscosity all of the new matrix systems display very good impregnation and wetting properties even during rapid mold filling processes. Depending on the tool temperature chosen in the case of the thermosetting systems a fast

Fig. 5. Energy absorption of driver's seat backs made from PA6 with short fiber reinforcement (GF), long fiber reinforcement (LF) and a hybrid of short glass fiber with UB tape inserts (CFRT) respectively: During drop tests the energy absorption over time was recorded (all measurements at 23 °C)



Bodywork and Structural Components Using RTM

Through the polymer applications being targeted by the automotive industry for bodywork and chassis, which should make the next step change in weight reduction possible, new demands are being placed on the performance of materials as well as their processability. It was for this reason that BASF set up the cross departmental and material Lightweight Composites Team in 2011. They are investigating the potential of the three polymer matrix components epoxy resin, polyurethane and polyamide in respect of the mass production use of continuous reinforcement in resin injection processes. In this way the company can make targeted use of its extensive portfolio of all three classes of material along with the associated processing know-how in partnership with representatives of various parts of the automotive value added chain and create synergies.

Fiber Composites with RTM: One of the processing technologies behind the



Fig. 6. The prototype SUSCO 1.5 seat from Faurecia was developed jointly with BASF and uses continuous fiber thermoplastic tapes in the seat back (white in the picture) which in a second process are overmolded with a special polyamide (black seat back parts). The replacement of the existing metal structure in the seat backs with a single piece polymer component reduces the weight of the back by about 20 %

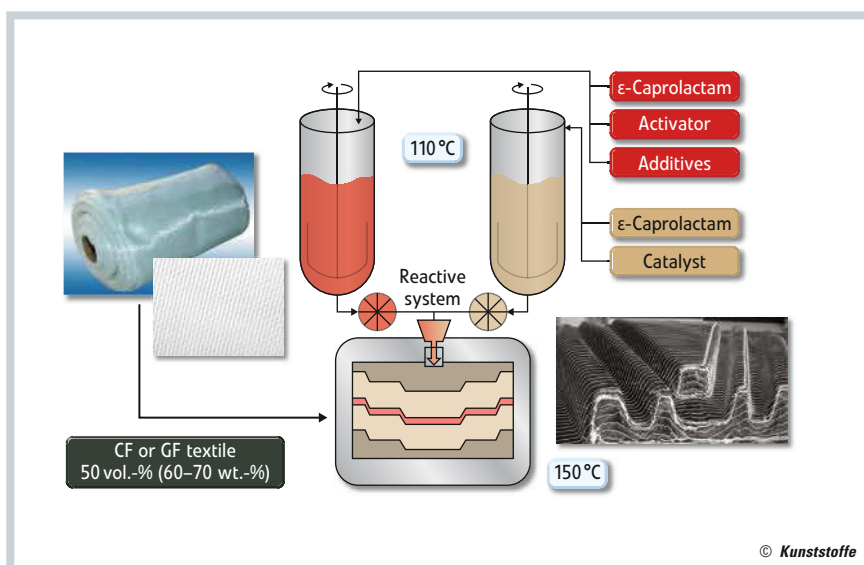
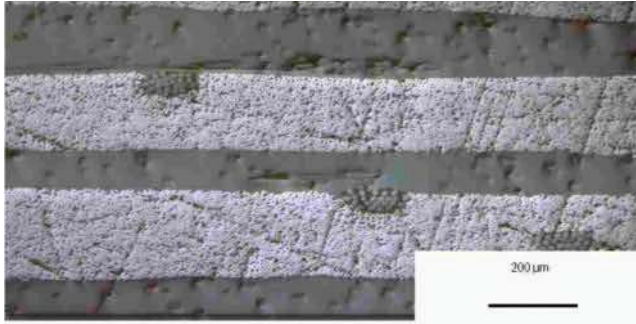


Fig. 7. Resin Transfer Molding (RTM) process sequence for the case of polyamide

cross-linking reaction occurs whilst the thermoplastic polyamide polymerizes and crystallizes in a short period of time (Fig. 7). Alongside the mechanical performance of the finished fiber composite part the good flow properties of the matrix systems (even with long flow paths), the degree of impregnation and the short curing time of the polymer components are highly important factors for all three material types (Fig. 8).

BASF already offers solutions based on epoxy resin and polyurethane systems under the brand names of Baxxodur and Elastolit R. Both thermosets use innovative curing mechanisms so that they cross-link within a few minutes. They can be processed on conventional high and low pressure equipment. The new polyamide systems, which are currently →

Fig. 8. Scanning electron microscopy: The picture shows the multilayer construction of a unidirectional carbon fiber epoxy laminate. What can be identified is the layer thickness homogeneity and high quality of impregnation



under development, are based on the very low viscosity caprolactam, a precursor of PA6, and highly advanced activator and catalyst systems. In contrast to classic PA processing they react only once they are within the mold. These thermoplastic composite materials can then be molded, welded and recycled. The large effort that BASF has put into the development of the three systems is aimed at additional reductions in cycle times and improved processability. It is accompanied by the extension of simulation tools for the prediction and component layout of even such complex continuous fiber composite structures.

Continuous Fibers for Structural Components: Continuous fibers are already being used in aircraft construction, wind energy generation, plant construction, prototyping and in low volume automobile applications. Carbon fibers offer a very high specific stiffness and strength as a reinforcing material and are therefore of particular interest. In comparison glass fibers offer a large potential as widely available cost effective materials: There are also new systems which show that the performance envelope of this traditional reinforcing material has in no way been fully exploited yet. The possibility of combining the various matrix polymers with the various types of fiber and textile architecture offers a high level of design freedom (Fig. 9). However, alongside the performance of the reinforcing materials the mass production suitability and cost effective processes based on fast matrix systems are important factors for the market success of continuous fiber reinforced components.

In contrast to injection molded components with local continuous fiber reinforcement the performance of such RTM components is even better since the continuous fiber reinforcement extends over the entire part. The initially dry fibers and rovings can also be processed to tailor made pre-forms and large 3-D components. Amongst these are highly loaded structural vehicle components as well as

mounted parts such as doors, tailgates and roof modules (see Title picture).

Up to now RTM technology has been used for low volume runs in the luxury vehicle sector such as Porsche spoilers or the roof of the BMW M3 and racing cars as well as trucks and agricultural or construction machinery. In those applications roofs, cowlings and cabin parts are produced in 2K epoxy systems with glass and carbon fibers. At between 10 and 20 min, depending on the part size, cycle times with conventional matrix systems are however still rather long.

Roof Module as a Concept Study: The first demonstration part based on the various materials from BASF suitable for RTM is the convertible roof module made up of several sections in a sandwich con-

struction with carbon fiber reinforced cover layers and a polyurethane foam core (Fig. 10). This roof segment forms the forward part of a three section RHT folding roof concept (RHT: retractable hard top) which was conceived and designed by EDAG GmbH, Fulda, Germany, as a feasibility demonstrator for a generic fiber composite sandwich concept with system components from BASF optimized with each other.

The central layer of the demonstrator sandwich structure is a closed cell PUR structural foam from the Elastolit D range. It serves as a low weight separator for the laminate cover layers which leads to an exceptionally high component stiffness. In addition it gives the roof module good insulating properties. On the exterior the component is protected from UV radiation and other environmental influences by a paint that contains the BASF Tinuvin CarboProtect additive.

Upscaling this to a mass production capable process will require a pre-formed foam insert containing all the additional inserts, covered on both sides with the chosen textile structure that is laid into the mold and fully impregnated in a single operation. The PUR foam system specially developed for this by BASF has a



Fig. 9. Various glass and carbon fiber textile structures based on wovens and non-wovens (left); various RTM fiber composite laminates based on polyamide, polyurethane and epoxy resin (right)

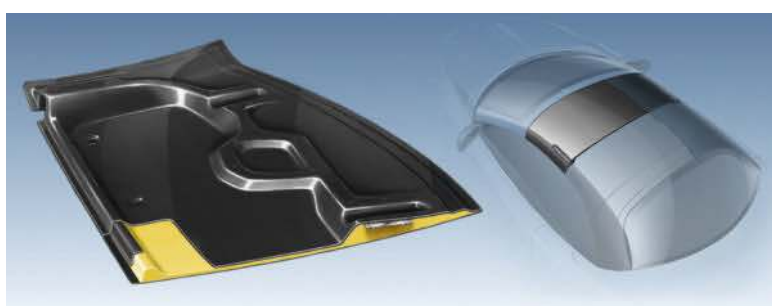


Fig. 10. RTM process demonstrator: The convertible roof module concept study is made in sandwich construction with carbon fiber reinforced cover layers and a polyurethane foam core

high pressure and temperature resistance as well as low density. This ensures that the foam core is not compressed during the injection phase.

The RHT roof segment as a fiber composite sandwich concept weighs 2.6 kg in total, which represents a weight reduction of 40 % compared to an aluminum construction and more than 60 % compared to one made from steel, whilst offering a comparable loading capacity under all typical design loading cases for vehicle roofs.

Conclusion

With light but sophisticated high performance fiber composite components and the associated composite raw materials it is possible to replace even more metal, save weight and thus, independent of the vehicle drive system, reduce energy consumption and CO₂ emissions still further. In regard of cost-benefit considerations various matrix materials, fiber types, reinforcing techniques, joining technologies, predictive modeling and processing technologies are currently being researched and developed in parallel and rigorously investigated for their suitability for mass production. Depending on the customer requirement profile one or the other of these system solutions will be used so that it is likely that several technologies will establish themselves in the marketplace side by side. Raw material manufacturers, part suppliers and OEMs will have to work together to establish the necessary competence required to fully exploit the potential they offer. Without such multiple material systems the next leap in automotive lightweight construction will however not be possible. ■

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