VDI

K

KUNSTSTOFFTECHNIK

Plastics in Automotive Engineering

KUNSTSTOFFTECHNIK

Plastics in Automotive Engineering

Herausgeber: VDI Wissensforum GmbH
VDI-Gesellschaft Materials Engineering

Bibliographische Information der Deutschen Bibliothek
Die Deutsche Bibliothek verzeichnet diese Publikation in der Deutschen Nationalbibliographie; detaillierte bibliographische Daten sind im Internet unter http://dnb.ddb.de abrufbar.

Bibliographic information published by the Deutsche Bibliothek
(German National Library)
The Deutsche Bibliothek lists this publication in the Deutsche Nationalbibliographie (German National Bibliography); detailed bibliographic data is available via Internet at http://dnb.ddb.de.

Printed in Germany

ISBN 978-3-18-234348-6

Foreword

Engineering plastics, fiber-reinforced composites and multifunctional plastic composites provide ongoing support to the modern automotive industry today.

In many cases multi-functional tools and automated processes make particularly economic system solutions possible. Additive manufacturing in combination with plastics already has a great potential today for producing individual, tailor-made component concepts, above all for small production runs.

Lightweight construction, an attractive look and feel for the interior, and active and passive safety stand right at the forefront of new automotive developments today.
Innovations in plastics technology have a direct influence on tomorrow's vehicle concepts. Mixed construction with plastic composites, natural fiber applications, overmolded and in-mold film laminated parts, LED- and OLED-based lighting technologies, and also optically and haptically optimized display and operating concepts make tailored system solutions possible in both passenger cars and commercial vehicles and thus secure in the long term the international competitiveness of the plastics and automotive industries.

The Association of German Engineers invites you to Mannheim on the 29th and 30th March 2017 for the annual international plastics conference 'Plastics in Automotive Engineering 2017'. Overview presentations on resource efficiency from research and the market, technical reports on innovations in plastics from the car and commercial vehicle sectors, as well as practical reports from plastics processing provide detailed information on the current state of the art in plastics technology in automotive engineering. An exhibition involving plastics producers and machinery manufacturers as well as an affiliated motor show with the latest cars and commercial vehicles provide a focus for an exchange of specialist information at the object itself.

May we cordially welcome you to Mannheim!

Prof. Dr. Rudolf C. Stauber

Table of Contents

Plenary Session

Interior

Exterior

Cost Reduction

Future Plastic Applications

Technology

Sponsor of gold:

Sponsor of bronze:

Future 2050: technological trends in an era of sustainability and smart machines

Dr. **U. Eberl**, SciPress, Höhenkirchen/Munich

Abstract

We are on the cusp of a new epoch. The climate of our planet is threatened, raw materials are in short supply. The century of oil is coming to an end and the world's energy supply must be switched over onto a new, sustainable basis. By 2050 almost as many people will be living in cities as there are today on the entire globe – and for the first time there will be more seniors than children and young people. At the same time, the era of smart machines is beginning with ever more powerful technologies of artificial intelligence. The smartphone was just the beginning: the Smart Car, Smart Grid, Smart Factory, Smart Health and Smart Home will shape every aspect of life in the future. It is a question of environmentally friendly energy systems, sustainable mobility, an energy-saving industrial sector with flexible manufacturing, and intelligent assistance for an ageing population.

1. The megatrends of the coming decades

Anyone seriously engaged in the subject of the future from now until 2050 should not let himself be swayed by ephemeral hypes or fashions. Much more important are global, long-term megatrends. These include demographic developments, urbanization, globalization, consumption of resources and energy, and the penetration of information and communication technology into all areas of life.

By 2050 the world population will have grown by a third to about 9.5 billion and of these there will be more elderly than children and young people. The number of people aged over 65 will triple from today's 500 million to 1.5 billion. In Germany already every third person is over 65, every eighth person over 80, and by 2050 the number of centenarians will have grown tenfold. The world is becoming a society of seniors – and this is the task of a century for many economies. Enormous burdens are thus placed on the pension systems and on the health systems as well. We need more prevention and early detection of diseases, more efficient procedures in health care, computers as assistant physicians, robot support during minimally invasive operations, but also in the Smart Home, and finally on the streets. Even 90- or 100-year-olds would still like to be mobile, but they will rarely be still driving themselves – the autonomous networked vehicle, the Smart Car, will be the solution of choice here.

At the same time, by 2050 almost as many people will be living in cities as there are on the entire globe today. The developing and emerging countries will have another three billion city dwellers, many of today's megacities will double their populations yet again, with enormous consequences for all areas of life – from mobility to building technology, the energy supply and health care. Gigantic urban conglomerations will arise, particularly in Asia, in which cities with 40 to 60 million residents will then coalesce. China will overtake the United States as the largest economy and also in other boom nations, such as Brazil, India, Mexico, South Africa and Vietnam, prosperity will continue to grow. The number of people classified as middle class will grow by more than a billion over the next ten to twenty years in such countries along – and thus too the demand for industrial products of all kinds as well as raw materials and energy.

The need for transportation – not least also due to internet mail order companies – globalization and the high importance of personal mobility can thus lead to a further enormous rise in freight transportation and the demand for individual mobility solutions. Just one comparison: in China today one person in ten has a car, in Germany every other person. But even today China's cities are plagued by congestion and emissions – the extremely high values for fine dust have led the Chinese Academy of Social Sciences to declare Beijing as 'unsuitable for human life'. Where would this end if the Chinese wanted to be as mobile as the Germans? And the situation in India, Brazil, Russia, Mexico and Indonesia does not look much better.

The solutions must be found in a combination of many innovations: electric vehicles with electricity generated from renewable energies, wisely distributed logistics centers in the cities and their outskirts, more freight carried by rail and – in some cases such as the transportation of medicines – even by air, using drones. For individual mobility, 'mobility on demand' is the keyword. In future it will be more a matter of using mobility packages than of actually possessing the vehicles. The goal is to network all modes of transport, be they buses and trains or rental bikes and rental electric cars. Via smartphone and internet the user will always have access to the latest information about the traffic situation and will know which means of transport to use to get from A to B the fastest and cheapest way.

In addition there are urban solutions, such as 'short-distance districts', as well as more teleworking thanks to broadband connections. In future many services, from product design to medical diagnosis based on laboratory data or computer images, can be handled from home just as easily from the office. Even when fast repairs are needed, parts do not always need to be dispatched. In the future it will be possible to fabricate many components on the spot using 3D printers – this has in the meantime become possible not only for plastics but also for gas turbine steel.

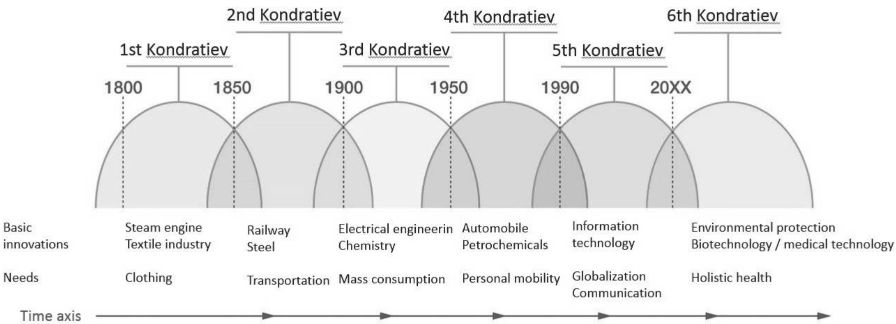


Fig. 1: Waves of innovation shape the world. The fifth Kondratiev cycle, today's age of information technology, is followed by the sixth cycle, which is determined by environmental and health issues (source: [1]).

2. Environmental health and human health

There are primarily three technological areas which will have a particular impact on our future over coming decades. Two of them can be summarized under the heading of 'holistic health': the health of our environment and the health of the people in a time of major demographic change. This concept of holistic health is also referred to as the sixth Kondratiev cycle, which, according to the forecasts of futurologists, will develop out of the fifth cycle, the current age of information and communication. These cycles take their name from the Russian economist Nikolai Kondratiev, who formulated this clear, if also greatly simplified, construct in the 1920s. Economic developments run in long waves of 40 to 60 years, beginning with basic innovations, continuing with the resulting growth in prosperity, and finally stagnating and being succeeded by the next wave.

What are the drivers behind the coming trend of 'human health'? When it is known that today around 40% of the cost of health care is accounted for by seniors older than 65 years and that this number will triple globally, it follows necessarily that the health systems of the future will only be able to remain financially viable by becoming more efficient and cost-effective. This pressure will result in a variety of innovations – from biomarkers for the early detection of cancer, cardiovascular disease and Alzheimer's disease to tele-medicine or sensors for monitoring health, whether at home or on the road. Last but not least diverse robot- and computer-based aids will be developed for the elderly in the Smart Home and the Smart Car.

The boom in environmental technologies – 'environmental health' – has several drivers: firstly, efforts to keep climate change within tolerable limits and, secondly, the increasing scarcity of resources. When the global population rises and in many countries prosperity also increases, then the demand will grow for technical products and thus also for raw materials. This will encourage energy- and resource-efficient products and manufacturing processes, recycling and a closed-loop economy. 'Cradle to cradle' and 'design to recycle' are important key phrases here – that is, to design products right from the very start to be environmentally friendly and modular in construction so that their individual components can be reused with no loss in quality or their waste materials can be used for new products.

In the meantime, there are many examples of biodegradable plastics, mainly in all kinds of packaging but also in paints, compostable seat covers, or adhesives, which can be broken down by bacteria and thus make individual components easier to recycle. Climate-neutral products from renewable raw materials will also gain in importance in the future, from bio-fuel made from plant waste to bio-plastic. Alternatives to the standard plastic ABS have accordingly been developed in pilot projects. These are not based on fossil fuels such as natural gas or oil, but on PHB (polyhydroxybutyrate), which can be produced from renewable raw materials such as palm oil or starch. The brittle PHB is softened by adding PPC (polypropylene carbonate) into which a high proportion of carbon dioxide from power plant waste gases can be integrated. Overall, more than 70% of the new mixture consists of sustainable plastics [2].

Carbon dioxide from power plant waste gases can be usefully employed elsewhere as well. For example, researchers have already demonstrated that with the aid of suitable catalysts, water and electric power – for example, the excess power from renewable sources – a high percentage can be converted into carbon monoxide or ethene. Other hydrocarbons or alcohols such as methanol can also be generated in this way. Compounds of this kind can then be used equally as fuels for vehicles or as raw materials for the chemical industry. In the more distant future, modules are even conceivable which can be used for house frontage cladding, capturing carbon dioxide from the air and converting it into valuable chemicals. Currently this is not economically feasible but when the introduction of carbon dioxide into the atmosphere as climate damage is given a clear 'price tag' this situation may change entirely.

Whatever solutions are found, ultimately sustainability must become a leitmotif of human activities over the next few decades, since if things carry on as usual, world consumption of raw materials and energy will at least double by 2050. Even today our ecological footprint is too large. We are using the earth's resources around 50% faster than they can regenerate themselves – a doubling of resource consumption means that we would need three earths instead of one by 2050.

The crucial questions are therefore whether it is possible to achieve economic growth while consuming fewer resources and whether climate change can still be slowed down. The answer to both questions is a clear affirmative – but it requires not only a major rethink in the head but also a paradigm shift in the global energy supply and the economic systems. As with the major demographic change, this is the task of a century but it is possible. It is all about a departure from the carbon age, about renewable energies, energy efficiency, intelligent power grids, recycling raw materials, eco-efficiency and a closed-loop economy.

3. A new era of electricity

Many problems can be solved by electricity from renewable sources such as wind, sun, water, biomass and the heat of the earth. It can be generated with an extreme degree of environmental friendliness, transmitted very efficiently even over long distances and converted into usable energy with only minor losses. Accordingly, electric motors are three to four times more efficient than internal combustion engines and the new LED lights around five to eight times more efficient than the old incandescent lamps. Enormous potential efficiencies can thus still be leveraged here, as in building services and in industry where optimized drive solutions make 60% cuts in power consumption possible.

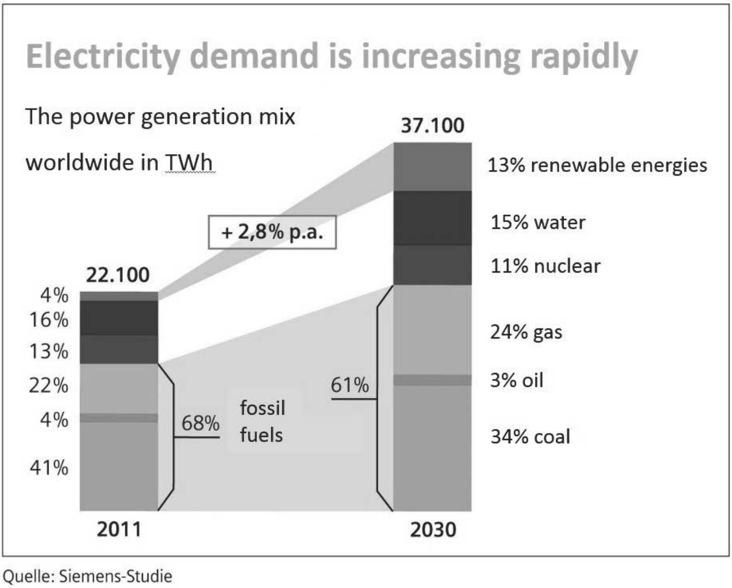


Fig. 2: The demand for electricity is increasing three times faster than the world population. The information and communication sector's demand for power will almost double to 1700 TWh each year and the share of power consumption taken up by the industry rise from 33% to 400% due to digitization and electric drives.

The trend is clear: we are on our way into a new era of electricity, because despite all gains in efficiency global electricity consumption is rising three times faster than world population, driven primarily by information and communication technology and by digitalization in industry. But this is good news since economic growth can be achieved with low environmental impact – assuming an ever-growing proportion of electrical power is obtained in future from renewable energies.

Even in the case of road traffic, we are experiencing a shift away from the oil age. The proportion of hybrid and electric vehicles will grow massively in coming decades, until most city vehicles in 2050 will be running on electric power. Moreover, they will then form an integral part of the power grid, as they not only load and save electricity but also can give it back, either to the grid for own consumption at home. They can for example fill up at night when there might be a lot of wind but little power is consumed, and give it back again at midday or in the afternoon when demand is rising and thus the price of electricity. Quick-charging systems and inductive charging (in other words, no cables) will also be part of everyday life. And with many of these vehicles the electric drive motors will be accommodated directly in the wheels. Each wheel can then be controlled individually. A vehicle of this kind can park transversely or even turn on the spot. Not only that but axles and gearboxes are no longer needed – designers are given unimaginable new possibilities for vehicle interiors, thus enabling entirely new levels of comfort, not least ideal for tomorrow's seniors.

4. Smart Machines – a thousand times more powerful than today

The third major trend in the coming decades, in addition to environmental health and human health, has already been massively underway since the 1990s as the fifth Kondratiev cycle: digitization, the penetration of information and communication technology into all areas of life. In the next 20 to 30 years we can count once again on a thousandfold increase in computing power, storage capacity and the data transfer rates of microchips. In the mid-1990s the most powerful supercomputer in the world managed about 100 billion operations per second; today that is achieved by a good smartphone, and we can expect another such performance increase by 2040. Today's supercomputers we carry in our pockets, at the price of a smartphone. To put it another way, what a notebook can do today for €500 a small chip can then do for €0.50.

In future, tiny sensor and communication elements will be fitted in everything, houses will be given sense organs like cars, which become mobile robots finding their way autonomously and communicating with other vehicles. The major trends in the automotive industry are electric, autonomous and networked. Tomorrow's Smart Cars will perceive the environment with their many sense organs, make contact with other vehicles and the infrastructure in contact in order to avoid congestion and accidents, and they will use their energy as thriftily and environmentally friendlily as possible. They will always be aware of the current traffic situation and know their owner's diary and preferences: his radio stations, social networks, sights or favorite restaurants.

Fig. 3: Electric, autonomous and networked – tomorrow's Smart Cars are independent robots on wheels (Source: [2]).

We will in the future meet smart machines everywhere [3]. By this I mean all machines, from smartphone to the autonomous vehicle, which have a certain level of intelligence. That is, for example, they can speak and listen, understand gestures and facial expressions. interpret texts, photos and videos, and are able to learn – by observing, by imitating, by being rewarded. In a few years we will be able to switch our cars to autopilot on the motorways, and by 2030 on the highways and in the cities. Even driverless trucks – including those connected together by an electronic drawbar – will be part of everyday life, as well as driverless electric taxis. Automatic shopping trolleys will deliver purchases curbside. Drones deliver urgent packages by air. With our smartphones we hold genuine conversations and in the kitchen machines prepare our meals.

With 'deep learning' systems, which on the basis of neural networks recreate the way the brain functions, researchers have already achieved great success in recent years, especially as regards recognizing image content and understanding speech. Scene analyses are already even possible with autonomous vehicles. This means that the car can not only recognize objects such as buildings, trees, posts, traffic signs or cyclists recognize but can also assess situations can estimate – for example, based on the head movement and the posture of an individual at the edge of the road it can make a probability statement as to whether this person wants to cross the road or not. The computer has learnt this with the aid of thousands of video images with the corresponding traffic situations. Other smart machines, such as IBM's Watson computer system, can even be fed with questions in everyday language for particular fields of knowledge. Watson is already providing support to physicians in cancer diagnostics, to pharmaceutical companies in the development of drugs, to bank consultants regarding investment strategies or to car companies in the analysis of workshop reports.

Smart grids will in future balance power supply and demand for millions of energy generation plants and consumers, and also combine the heat, electricity and gas networks. Semi-autonomous buildings, with solar panels on the roof and storage batteries in the basement, team up to form virtual power stations and via virtual exchanges carry out energy trading. In the wider environment, the smart cities, sensors measure all kinds of energy and water consumption and also traffic data and emissions. A 'city cockpit' then intelligently summarizes this information, prepares forecasts and makes suggestions for optimizing the systems.

In smart factories, people work hand in hand with robots. New products are designed on the computer in the global developers' association, tested in virtual space together with their production, the purchasing and delivery processes optimized and the product then possibly even printed with a 3D printer. Maintenance engineers will no longer be active at fixed time intervals but only when the computer reports that the wind turbine, the traffic lights, the truck or the train needs maintenance because sensors have detected irregularities which in a few days or weeks would lead to failure.

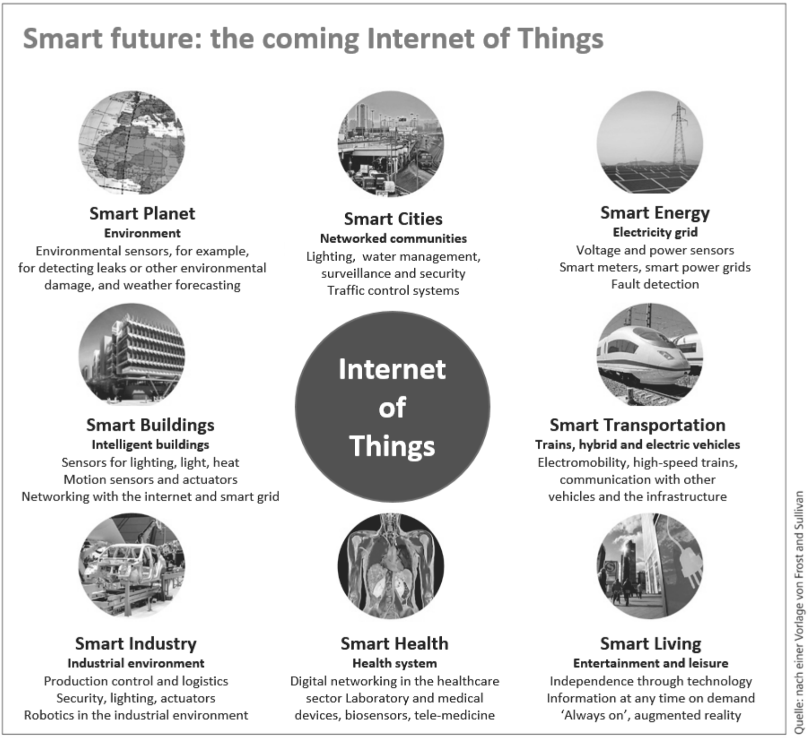


Fig. 4: The future Internet of Things is full of smart machines. The smartphone was just the beginning: Smart Transportation, the Smart Home, Smart Industry, Smart Health even entire Smart Cities will follow.

Sowing, fertilizing and harvesting machines drive autonomously in the fields. In warehouses people no longer go to the shelves but the shelves move under computer control to a station where currently humans but in future robots take the goods and make them ready for dispatch. Even in hotels, museums and shops robots will serve and provide information. Only the household electronic butler will be several decades more in coming: its tasks are simply too complex and it is also supposed to be affordable.

I am convinced that true revolution of smart machines is yet to come. It will properly pick up speed when the four most powerful development strands come together: the deep-learning processes of image, speech and text recognition, the cognitive computers which can even process knowledge, the development of robots and autonomous vehicles and, last but not least, automation and digitization in production – in other words, what has become known to us under the keywords of Industry 4.0 and the Internet of Things.

[1] Eberl, U., *Zukunft 2050 – wie wir schon heute die Zukunft erfinden*, Beltz & Gelberg, Weinheim (2013, 5th edition) and also www.zukunft2050.wordpress.com

[2] Siemens AG, Zukunftsmagazin *Pictures of the Future* (issues 2001-2015) and also on the internet www.siemens.de/pof

[3] Eberl, U., *Smarte Maschinen – wie Künstliche Intelligenz unser Leben verändert*, Hanser, Munich (2016)

Sewn-covering lamination for the instrument panel:
from the discontinuous to the continuous process

R. Kurz, **S. Hobelsberger**, **H. Auer**, BMW AG, Landshut

Abstract

The BMW Group has in collaboration with the Austrian tool and machinery manufacturer 3CON GmbH developed a concept which makes possible the continuous production of instrument panels in a sewn-covering lamination process. This development was triggered by the growing demand of the market for optional equipment variants with the very best look and feel for the automotive interior. A process which originally took more than ten minutes of cycle time and involved a great deal of manual work has been transformed into a process ready for high-volume production.

1. Requirements

While the need for product differentiation was still mainly covered by motorization variants in the 1950s and 1960s, in the years which followed there was an increasing desire for additional options for upgrading the product. One of the leading characteristics of the 1970s was the 'driver-oriented' cockpit. Likewise in recent years the focus has been on new materials, new looks and a more exclusive feel. Buzzwords such as pressure and touch haptics, or tactile and visual appeal have found their way into the industry. This can easily be seen in the example of the BMW 503, manufactured in the 1950s, as compared with the current 3 Series today.

Fig. 1: Development of the cockpit from the 1950s to the present

There is no doubt that pure functionality stood in the foreground earlier. A high perception of quality can in particular be secured by means of technologies in which the surfaces are produced by complex methods. Today, therefore, physical comfort, an appealing impression and high quality perception are prioritized since demands on the passenger compartment have increased immensely over the years. The cockpit of the future should therefore represent an enclosing frame for the driver controls. Over the years there has been increasing success in arousing emotions via the appeal of different materials.

Fig. 2: Requirements for a modern cockpit

An innovative and at the same time efficient process for the high-volume production of instrument panels with high-quality surfaces, especially in the premium segment, has moved increasingly into the focus of development activity.

2. Process currently used at BMW

The development of the procedures used in sewn-covering lamination is best shown in the example of the 7 Series:

Table 1: Stages in the development of sewn-covering lamination

1995	Pre-fixed externally and then laminated by means of a membrane with a cycle time of about 12 minutes
2008	Pre-fixed internally and then laminated by means of a hard mold with a cycle time of about 5 minutes
2015	Pre-fixed internally and then laminated by means of a hard mold with a cycle time of about 140 seconds

The cycle time of 140 seconds in 2015 is also state of the art at the present time. For this reason, this method should be examined a little more closely.

The underlying machine and tooling concept is based on a press with a rotary lower table. Two lower molds of identical design are mounted on the rotary table and one upper mold on the top part of the press.

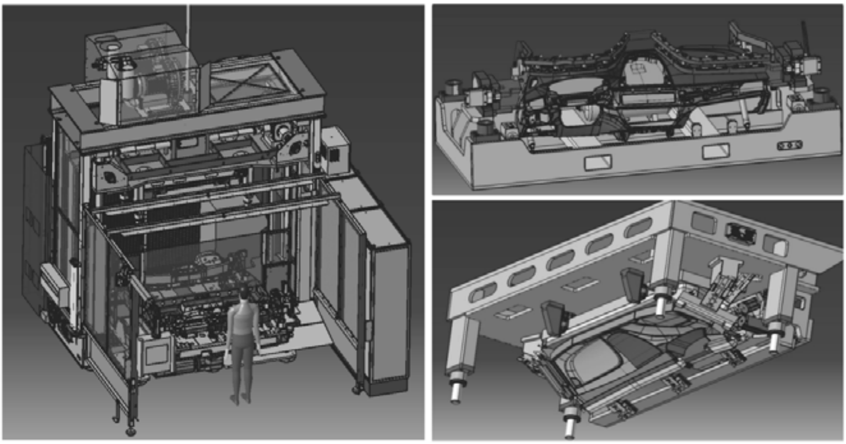


Fig. 3: Rotary-table machine for integrated pre-fixing

With integrated pre-fixing of the sewn covering followed by hard-mold lamination, the carriers are first wetted with adhesive in a spray booth. The sewn covering is then pre-fixed to one of the lower molds while the other stands in the production position. This decouples the insertion process from the lamination process. When the lower mold with the pre-fixed sewn covering then swings into the press, the lamination and edge-wrapping processes start. The adhesive joint is heated through the decorative material by the hard mold. This leaves almost the full 140 seconds available for the two processes of pre-fixing and of heating and laminating.

3. Possible solutions for high production quantities

Since the high-quality look of the sewn coverings is now no longer appreciated solely in the 7 Series models but also in the 5 Series, the X Series and increasingly in the 3 Series as well, considerably higher quantities will be produced in the future.

The first logical approach here lies in increasing the number of machines and molds in order to cope with these quantities. This approach does not involve any great risk since a tried and tested concept can be relied on. However, it inevitably means high space requirements, major investment in machines and tools, and a high staffing requirement.

Producing large quantities in all conceivable variants and with process reliability calls for a concept which is coherent in itself and combines all necessary process steps in one continuous sequence. Carrier, adhesive and sewn covering must be brought together in the right combination; here as few handling steps as possible should be aimed at in order to be economically attractive for high-volume production.

In a workshop BMW has thus come up with a possible scenario of what the production of sewn-covering laminated instrument panels might look like in the future.

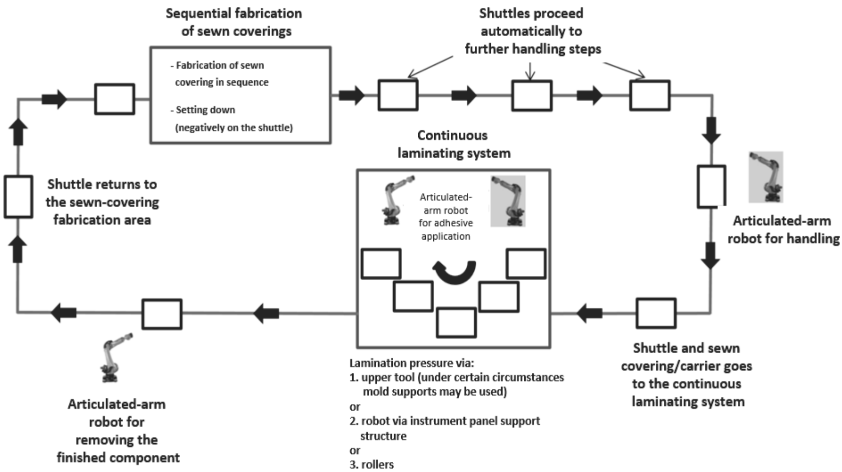


Fig. 4 : First approaches to continuous production

In collaboration with the 3CON company the first step was to extract the continuous lamination process from this overall sequence and redesign it, aiming at a 35 second cycle. The principle of a rotary table machine was selected and the process steps in a continuous revolving cycle decoupled even more from each other in order to resolve production bottlenecks.

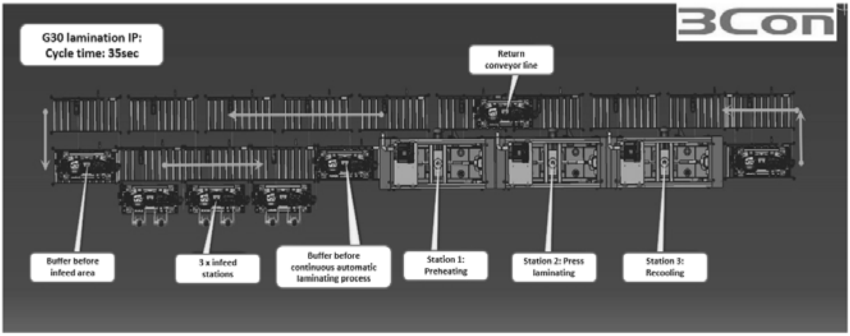


Fig. 5 : First concept for the continuous lamination process

The advantages of continuous production in the form of a single production line are obvious. Better synchronization with other processes is the result of shorter cycle times and this brings logistical benefits in the just-in-sequence production mode. Arrangement in a single line with concatenated process steps means a small footprint together with low personnel requirements. The modular layout means it is possible to respond flexibly to increases in capacity.

Shortening the cycle time from the previous 140 seconds or so to 35 seconds came up against two basic challenges in addition to the numerous automation tasks. Firstly, the sewn covering still had to be fixed by hand, and the time required for this must be available without fail. Secondly, the adhesive has to be heated right through the sewn covering. Both issues can only be solved by a further separation into individual steps.

4. Continuous production

The continuous laminating process requires a breakdown into the following steps:

- Pre-fixing station
- IR pre-flashing station
- Hot pressing station
- Cold pressing station
- Automatic removal

In the first step, the carrier and the sewn covering are placed on the lower mold. The orientation of the seam is facilitated by a seam blade which remains closed in all subsequent process steps. The moving walkway for the operator which moves in synchrony with the lower mold gives operators the time they need to fix the sewn covering as best as possible.

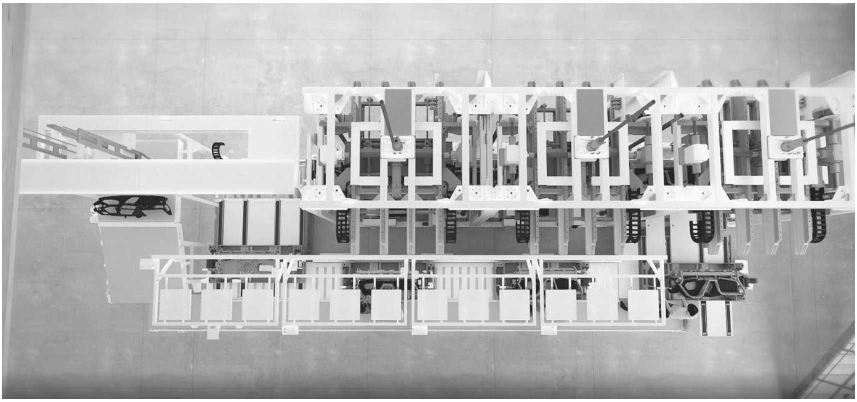


Fig. 6: Layout of the continuous laminating system

The operators then go back to the start of the walkway and repeat their passage through the station.

At the end of the walkway the lower mold moves into the IR pre-flashing station where infrared radiators preheat the adhesive joint through the decorative material.

The lower mold then 'shuttles' on into the hot pressing station where with the help of a hot upper mold the temperature required for activating the adhesive is established and also the compression force required is applied from both sides.

After the hot pressing station the lower mold travels into a cold pressing station where the adhesive joint is cooled by means of a cold upper mold in order to secure a permanent good bond.

Upon exiting the cold pressing station the finished instrument panel is removed by an automatic handling system and placed on a conveyor belt. The lower mold then returns to the beginning of the operator walkway. In this way, up to 8 molds can be accommodated in a single system.

5. Outlook

In addition to the production line we have described, which has already been set up for the BMW 5 Series, concepts already exist which will give a great flexibility to an instrument panel production line of this kind. For example, left-hand- and right-hand-drive components or even different models will be producible on a single production line without the need to change the tooling. Solutions in this regard include sliding tables or rotary upper tables in the heating and pressing stations, or even rotatable lower molds which cover both left-hand- and right-hand-drive components.

In addition, the production line can if necessary be combined with a tool-changing station in order to provide maximum flexibility.

Further developments go towards a further reduction in cycle times aiming at 30 seconds, and an expansion of the continuous process to include the remaining process steps in the production of instrument panels, such as concatenation with fabrication of the sewn coverings, the injection-molding process for the carrier, and the application of adhesive.

References

All information is based on internal documents, records, drafts and presentations of the BMW Group and the 3CON GmbH company.

Methodological further development of weight reduction in vehicle interior trim parts

Current and future opportunities from an automaker's perspective

M. Steinbach, **J. Maier**, Adam Opel AG, Rüsselsheim

Abstract

The following contribution considers the motivation for weight reduction and describes the requirements made of trim parts in the vehicle interior. It presents two approaches to efficient weight saving:

- Possibilities applicable in the short term, such as the use of natural-fiber carriers in the case of 'enhanced' (laminated) components, the selection of materials, and the wall-thickness design in the case of 'Mold-in-Color' parts

- Possibilities applicable in the medium and long term, such as the further development of thin-wall injection molding not only by the application of new construction and simulation methods but also by the use of new technologies and materials.

In this way improvements between 10% and 25% can be achieved overall.

1. Importance of vehicle weight and specific requirements for selected interior parts

What motivates us to reduce weight?

In the automotive sector, reduction in vehicle weight plays a central rôle. A high vehicle weight has a negative impact in several areas, the most well-known of these being driving dynamics and fuel consumption.

At the latest since the financial crisis of 2008/2009, with the corresponding impact on fuel prices, efforts to reduce vehicle weight have markedly intensified. In addition to this field of discussion, the demands made of vehicles have continually increased over the years, not least due to demands from consumer organizations which resulted in weight increases which had to be compensated.

Weight reduction depending on the material families

In areas of the vehicle which primarily function with metal materials, steel components are being increasingly replaced by metals of lower density, plastic-based solutions or hybrid approaches.

As regards the field of trim parts in the vehicle interior which already mostly use plastics, the demand for weight reduction brings up new challenges. Various alternatives are available here, starting with material selection within the context of the manufacturing processes already used for a component, and going as far as changing the manufacturing processes. These alternatives cannot however be selected freely and without restrictions since functional and commercial requirements must be considered on an equal footing in development work. This means that the material and production method must be selected very carefully and the best possible balance achieved between weight, material, process and costs.

Requirements made of vehicle interior trim parts

Vehicle interior trim parts serve to boost the quality of the passenger compartment. Surface materials are therefore selected which improve the vehicle area corresponding to these components both visually and also in regard to perceived quality. Various differentiations are implemented here, oriented not least by the vehicle segment and the position of the component.

These enhancements do not however represent more than a minor part of the requirements made of vehicle interior trim parts. Also to be taken into consideration are:

- Weight
- Material
- Surface quality
- The manufacturing processes available
- Static loads
- Passenger protection requirements as required by legislation
- Vibration and damping properties
- Ergonomic requirements (HMI)
- Component assembly, and
- Logistics.

2. Short-term possibilities in the example of a door panel

2.1 Possible selections

Basically, trim parts can be assigned to two categories:

- Components with an enhanced surface, and
- Mold-in-Color components (injection moldings with a textured surface).

Components with an enhanced surface

With enhanced (laminated) components a distinction is drawn between whether the surface should be improved by application of a paint or by the use of decorative materials, such as fabric, a PVC or TPO film.

If the choice falls in favor of decorative materials instead of a paint, it is possible to use carrier materials virtually independently of the visible surface. With parts of this kind, weight reductions can accordingly be achieved not only by the selection of the raw material but also by which production method is selected and, associated with this, by using raw materials of lower density.

It should be noted that with components like this a careful selection of material and manufacturing process is essential. Without paying due regard to the weight-specific parameters (such as film thickness, weight of the natural fiber mat), the weight limit of an optimized pure injection molding would otherwise rapidly be reached. This would, for example, be the case with a natural-fiber application if surface films were to be selected which, due to the texturizing process (IMG), would result in a greater thickness and thus a higher weight.

This rules out substitution of pure injection moldings for reasons of weight reduction. If however an enhanced surface is wanted, a considerable weight saving as compared with plastic can be achieved by using natural fiber as the carrier material.

Mold-in-Color components ((injection moldings with a textured surface)

With Mold-in-Color components the possibilities for weight reduction are limited. What is immediately available are the selection of raw material and the wall-thickness design.

Structural foam molding would be the variant of choice from the various injection-molding methods. It should, however, be noted that there are restrictions on its use with Mold-in-Color components. With textured components for immediate use in series production this reduces possibilities to the selection of the raw material and the wall-thickness design.

With the selection of raw material, the component weight can be reduced by up to 9% via the density of the raw material.

Reducing wall thicknesses also means possible weight reductions of up to 8%. This value refers to a flat part with no elements on the back side, and also depends on the initial wall thickness. The corresponding limitations on rigidity will also have to be accepted.

A comparison of the results of the density and wall-thickness reduction shows that the density of the material would have to be reduced from 1.03 g/cm³ to 0.94 g/cm³ in order to achieve the same weight reduction as would result from reducing the wall thickness from 2.5 mm to 2.3 mm. Depending on the availability of material, selecting a lighter material would give greater flexibility in weight reduction than by reducing wall thicknesses. Here, however, constructive measures are necessary, as described in the next section.

2.2 Impact of the selected weight-reduction method on component design, tooling and manufacturing facilities

Components with an enhanced surface

The most comprehensive variant for weight reduction are the enhanced (laminated) components. In this regard, various constraints on construction are to be observed, depending on the choice of carrier material and the manufacturing processes associated with this. These concern, among other things, requirements regarding minimum radii, additional drafts, and depths of draw. With natural-fiber carriers, undercut areas are a special challenge which, depending on the desired surface shape, call for additional components.

Depending on the materials and components contours, manufacturing components of this kind can turn out to be a vary complicated matter and entail multiple manufacturing steps.

In this light of this complexity, manufacturing methods of this kind are less attractive possibilities for substituting for injection moldings in the low-priced segment. In these segments the preference would be to optimize components within the possibilities of injection molding.

Mold-in-Color components

- Reduction in weight by wall-thickness reduction

Wall-thickness reduction in the case of Mold-in-Color components as a weight optimization measure can only be applied as an across-the-board reduction when there are no special requirements regarding rigidity. This method can be applied when rearside elements do not have load-bearing and support functions to perform and can thus be reduced in thickness (prevention of sink marks).

If rearside structures with a defined stability are required, the visible surfaces in these areas will be provided locally with adjusted wall thicknesses. These local wall-thickness adjustments must be carefully defined in close reference to the mold design. Generously dimensioned transitional areas reduce the risk of differences in the degree of gloss. Should several of these wall-thickness changes occur in succession in narrow areas, it may be necessary to dispense with a wall-thickness reduction in the interests of the smoothest possible flow of the melt.

Depending on the load case, mechanical loads require a certain rigidity of the component. In combination with a wall-thickness reduction an assessment should be made as to whether the loss of rigidity can be adequately compensated by an appropriate rearside structure or whether to forego wall-thickness reduction in the critical area. Without further surface treatment or other additional measures, fiber-reinforced materials are not a possibility with Mold-in-Color components.

Furthermore, components with a reduced wall thickness require greater care in the design of the injection molds. The number, position and design of the gates are of greater importance. In addition, it may make sense to take steps to ensure the melt is introduced at every single gate in a selective and controlled manner. Such hot-runner systems are available from various manufacturers and can also be evaluated in a simulation-based examination of the injection-molding process.

- Weight reduction via a lower raw material density

Selecting a material with a lower density is a possible alternative to wall-thickness reduction.

In contrast to wall-thickness reduction, this approach has the advantage that weight reduction completely extends over the full surface of the component. With complex components, this in a direct comparison yields advantages in constructive design and in mold design and also a greater weight-reduction potential.

Component design is less markedly affected and under known criteria can be implemented with virtually no changes. The less favorable thermal expansion behavior of such materials means that fairly large gaps and distances from adjacent components cannot be avoided. In the case of assemblies with several different materials their thermal expansion coefficients should in particular be assessed in general terms and with regard to unwanted effects, such as the bimetallic effect.

With this approach, the design of the tooling is less strongly affected due to homogeneous wall thicknesses than is the case with wall-thickness reduction.

3. Thin-wall injection molding as a further development of thin-wall technology

3.1 State of the art

As shown in the first section, thin-wall injection molding with conventional approaches can offer good weight savings of up to 10%. However, attempts have been made to achieve considerable increases in possible savings by applying new design and simulation methods and also by using new technologies and materials. Development work is at present concentrating on vehicle interior trim parts made of polypropylene, with a classification into three groups (Figure 1):

- Simple trim parts

This type of trim parts are components whose main function is to cover body panels (for example, trunk or rocker panels).

- Trim parts with a safety function

This category of trim parts principally includes body panels, supplemented by important passive protection functions. In many cases there is interaction with other protection systems, such as airbag systems.

- Trim parts with complex safety features

In the case of this group of components, the actual 'covering' function is a secondary function which is extended by further functions such as structure formation, accommodation of other components, active integration of protection systems, as well as high optical requirements. A typical member of this category is the dashboard.

In all three groups polypropylene (PP) is currently the most popular basic material, although different material classes of PP are assigned to the groups. In addition, the components must deploy their functionality over a wide temperature range from -40 °C to 80 °C, whereby the requirements made of the material are once again increased significantly.

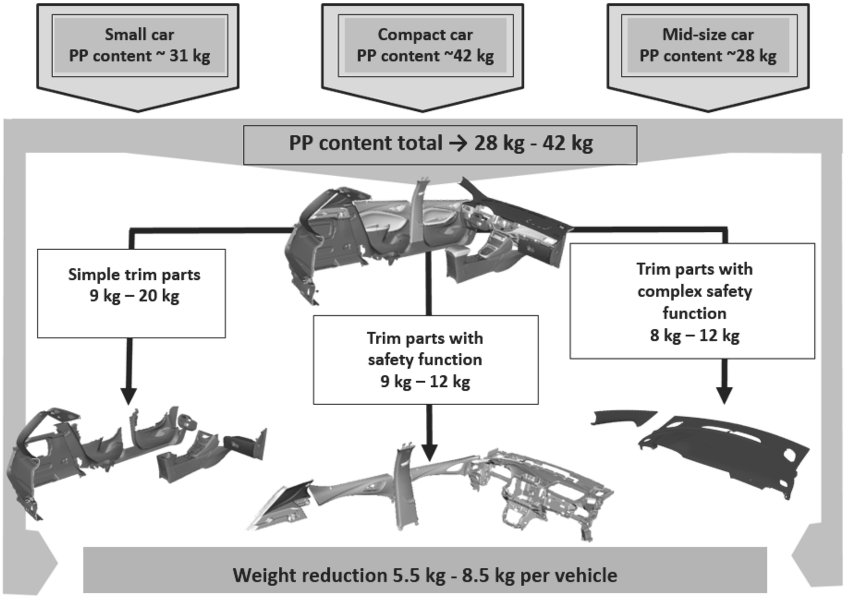


Fig. 1: Classification of the amounts of polypropylene in vehicle interior components and their average potential for weight reduction [1]

3.2 Further development of thin-wall injection-molding technology

As with conventional thin-wall injection molding, weight savings are primarily achieved by thickness reduction. The reduction in wall thickness is carried out much more aggressively, and in some cases wall-thickness reductions of up to 40% are sought. Depending on the component, this means that wall thicknesses in some areas are reduced to as little as 1.5 mm. The following aspects need to be reassessed or interpreted here:

- Constructive design (filling and structural simulation)
- Material
- Process, and
- Mold.

Constructive design

The component design is one of the most important factors for achieving an optimal weight-saving potential. In this case it is advisable to know at a very early stage in component development the precise loads and stresses of a component. Even in a simple trim part, different load cases often have to be covered (for example, clip take-off, installation forces, dynamic loads). In the past, the rear sides of the components were designed as a simple distanced surfaces of the A side. Wall thicknesses were increased in order to accommodate the corresponding loads and stresses. Since large sudden changes in wall thickness are not permitted in conventional injection molding, this occurred over relatively large areas of the component. Considerable improvements are possible with thin-wall injection molding in that the B side is reduced to a technical minimum. The loss in rigidity which necessarily occurs should be compensated by an optimal design of the rearside ribbing structure. Load-oriented design is supported by modern filling and structural simulations.

Material

Reducing wall thickness calls for significant improvements in the material's flow characteristics if the mold cavities are to be fully filled. There are two different approaches here:

- Structural foam molding

In structural foam molding two process types are distinguished: physical foaming and chemical foaming. Structural foam molding raises the pressure inside the component and also improves the rheology of the melt.

Each method has its own advantages and disadvantages: with physical foaming the injection process is easy to control but the machine technology is more complex.

Chemical foaming can be readily used in conventional injection-molding machines but due to the greater complexity of process control the blowing-agent chemistry has a negative effect.

- Polypropylene with improved flow properties

Special material adjustments of the PP optimizes flowability to the point that thin walls are made possible. This method has a very beneficial effect on the surface quality, since no adverse effects arise from the blowing agent or from foaming. Disadvantageous is that the reinforcement of thinned areas by means of ribbing can only be done in the gating conditions applicable for conventional injection molding. This means a reduction in weight-saving potential as compared with structural foam molding.

Process

In injection molding a variety of parameters influence the filling and the surface quality of the component without mentioning them explicitly. A good filling simulation is very important for the optimal definition of the gating conditions. Furthermore, the gating types, such as film gate or pin gate, have an influence on the filling behavior and especially on the surface appearance. Even the design of the gating sequence contributes to component quality, with a gating controlled by cascades proving to be advantageous. Alongside the gating parameters, the selection and the positioning of the hot runner system are also of crucial importance. Generally speaking, short hot-runner lengths tend to have a positive effect, especially with chemical foaming.

Tooling

As regards the tool design, care must be taken, especially with structural foam molding, that a needle-valve system is used to enable the foaming process to take place within the component. Because of the possible presence of blowing agent residues and the need to prevent corrosion from occurring, the use of higher-quality tool steels is recommended.

Furthermore, the use of variothermal heating systems and the integration of a gas counter-pressure system proves to be advantageous.

3.3 State of development of thin-wall injection-molding technology in the automotive industry

Numerous projects in the automotive industry are concerned with studying thin-wall injection-molding technology. Selected components include door sill plates (simple trim parts), B-pillar trim parts (trim parts with a safety function) and instrument panels (components with a complex safety function).

Here the scope of the project extends over several phases:

Component design, development of simulation methods and material models, tooling, definition of the rheology, and validation.

This comprehensive approach reduces to a minimum the development risk in series-production implementation.

Initial position

The results of development in the 'simple trim parts' category are presented below in the example of a door sill panel.

The component below shows the original design which has a constant wall thickness (Figure 2).

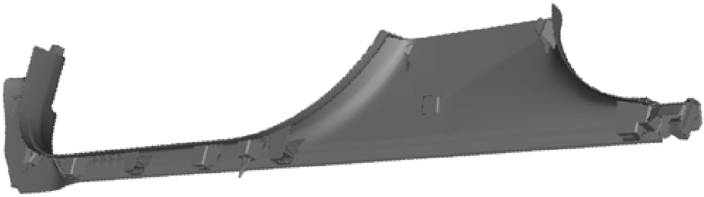


Fig. 2: Door sill panel [2]

Stress analysis

Figure 3 below shows selected load cases in the example of a door sill panel.

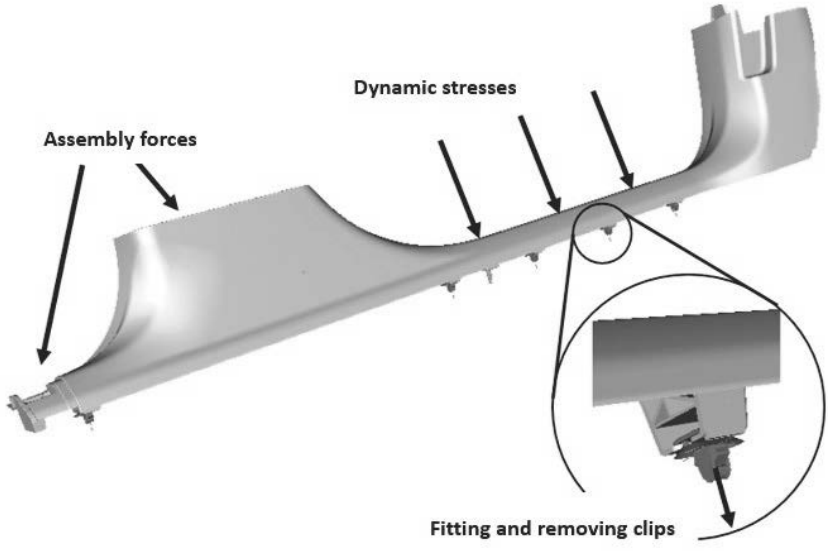


Fig. 3: Selected load cases in the case of a door sill panel [2]

Component design

Following the stress analysis, component design begins with the definition of areas to be thinned and with determination of the stiffness profile and the associated load-oriented ribbing design.

Figure 4 below shows the thin-wall construction, taking the example of the door sill panel.

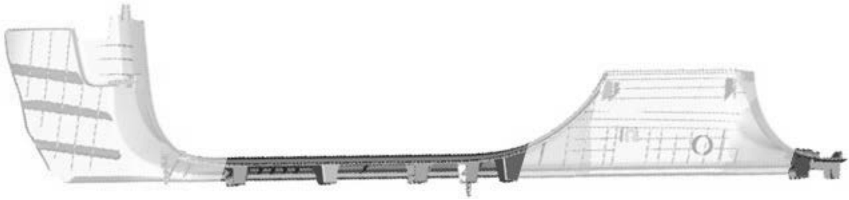


Fig. 4: Door sill panel in thin-wall technology [2]

Simulation and Moldflow analysis

Following component design, load-oriented simulation is carried out. With the aid of Moldflow analysis, critical areas are identified, remedial measures defined and an optimal tool design created.

Fig. 5 below shows a Moldflow simulation of the door sill panel.

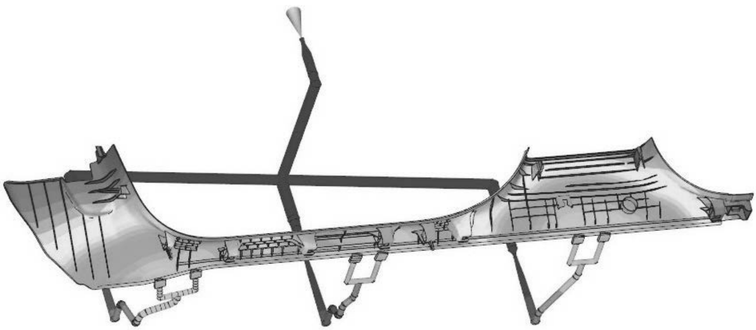


Fig. 5: Part of a Moldflow analysis in the door sill area [3]

Tooling and injection technology

Tool design commences on the basis of the information obtained. In injection tests the optimum rheological values are implemented analogously to the filling simulation. Furthermore, different material combinations are injected and evaluated.

Figure 6 below shows a thin-wall mold.

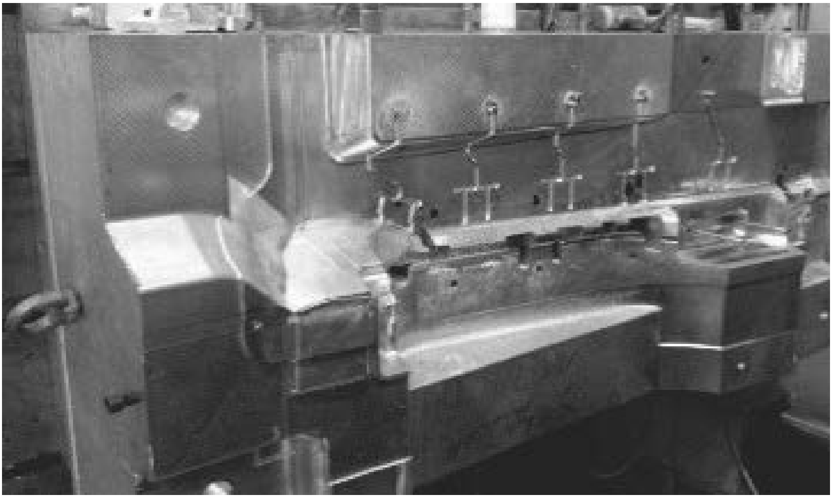


Fig. 6: Half of a thin-wall mold [2]

Results

In the case of the door sill trim, we succeeded in securing a weight reduction of up to 25% without impairing component functionality.

4. Summary and outlook

The first section of this contribution discusses the possibilities for weight reduction which are available for immediate use in series production. Two categories of component were distinguished: enhanced and Mold-in-Color components. The impact of these options on component design, tool design and process technology varies in complexity. Deciding which weight-reduction method is to be used depends on several factors and cannot be implemented across the board: coming to a decision requires a differentiation of 'requirements applicable to vehicle interior trim parts' and 'project-specific aspects.' The objectives laid down for the project determine the weighting given to these factors, the final definition of the component concept, and the possibilities for weight optimization which are thus available.

The further development of materials and also an optimal design of plastic components result in thin-wall injection molding technology offering a very effective approach to weight reduction. Compared to the previous design of the component, weight reductions of up to 25% are possible. In the field of mold technology and production technology there are numerous approaches which ensure a high component functionality combined with good surface quality. Modern simulation methods support the modeling and the design of thin-walled injection-molded components. Further potential is available in applying this technology to body components and also by transferring it to other plastics.

List of references

[1] General Motors: Project documentation for thin-wall injection molding, Rüsselsheim 2016

[2] General Motors: Technical documentation, Rüsselsheim 2015-2016

[3] General Motors: Simulation report for door sill panel; Rüsselsheim 2015

New vinyl ink and robotized digital printing process for the fine decoration of an instrument panel made by PVC slush molding

Dr. **N. Amouroux**, **M. El Fouzari**, IVY Group, Reims, France

2 Abstract

Since the Model T Ford, which was available in all colours provided it was black, consumer choice has increased steadily. Consumers can today configure their car online, by choosing from a set of technical and aesthetic options. However, when it comes to the instrument panel, the color black remains too often the main, or even the only choice. As the automotive industry shifts from mass production to mass customization, production tools should gain in flexibility and responsiveness. In order to address this trend, the IVY Group has developed specialty vinyl inks and a robotized digital printer able to print on curved surfaces, mold or parts, for the fine decoration of instrument panels, door panels and other parts made by PVC slush molding. This technology is ideal for widening the choice for consumers; it opens up new possibilities for limited editions, co-branding initiatives, facelifts and even personalization.

3 1 Introduction

The transition from mass production to mass customisation is encouraged by the digitalization of society. Online virtual configurators make interaction with consumers very efficient, enabling automakers to test in advance the demand for specific designs. Customization of the design is already a reality for other industries such as electronics, fashion or sport apparel. For example, NIKE proposes through the NIKEiD initiative the possibility of personalizing sport shoes, which are made to order and shipped in a few days.

Cars are made to order according to the choice of buyers, ranging from exterior color to engine type. In the interior, options are mainly limited to seat-covering type and electronics. The instrument panel, one of the largest parts in the interior, located just in front of the driver and passenger, is for most of the cars only available in black. The IVY Group conducted surveys in car dealerships, and found that both consumers and dealers were receptive to having

more personalized interiors. Consumers would prefer to choose from a closed list of options rather than to propose their own design.
For automakers, the possibility of easy customization of the instrument panels and other parts covered with skins by with PVC slush molding is an opportunity for limited editions, co-branding and facelifts without major changes in the shape.

TMG Automotive introduced inkjet printing on flat TPO performed by in-mold graining (IMG) for the Toyota Yaris [4]. This solution is limited to simple printed designs, as the printed image is deformed during the IMG process. In addition, printing cannot coincide with an embossed area. It suffers also from the limitation of TPO itself: limited depth of forming and poor tactile properties.
In contrast, PVC slush molding is a very flexible technology regarding design freedom, which gives a leather-like feel.

The IVY Group is the leading supplier of PVC slush compounds (PSC) for automotive interiors, with plants in France, Germany, Mexico and China manufacturing PSC under the trademark Nakan® DrySol. The IVY Group manufactures also specialty in-mold vinyl paint Nakan® SpraySol for production of two-tone instrument panels, with full respect of grain and the possibility of using a wide range of colors and effect pigments. To address the trend of growing customization in automotive interiors, the IVY Group has developed specialty vinyl inks Nakan® PrintSol and a unique robotized digital printing solution able to print fine decoration on curved surfaces. The combination of Nakan®DrySol, SpraySol and PrintSol offers a powerful and flexible toolbox to designers for enhancing automotive interiors with an unrivalled freedom, a prerequisite for mass customization.

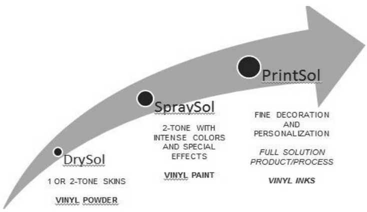


Fig 1: Product range for customization of the dashboard

This printing system can offer our industrial customers great flexibility since it allows decoration of the instrument panel by printing directly in the mold (in-mold printing) or by printing directly on the dashboard (post-printing).

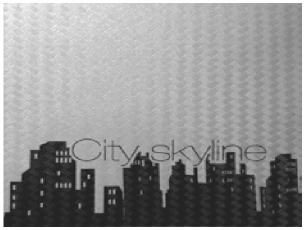


Fig 2: Artist’s view

Fig 3: In-mold-printed skin

For in-mold printing: decoration is printed within the mold and transferred from the mold to the skin after the slush molding process.
For post-printing: decoration is printed directly on the final part; this alternative printing process is useful forcustomizing at the very last step of the manufacturing process.

In this paper we will focus on the main technical challenges that we had to solve during the development of this mass customization solution, and also on a comparison of in-mold and post-printing solutions and a description of future developments.

4 Technical challenges

We can list the technical challenges in five points:
- Development of inks which meet inkjet printing process requirements
- Formulation of inks compatible with slush-molding high-temperature manufacturing processes
- Development of a highly accurate robotized printing process for printing onto embossed designs
- Development of a CMYK/multi-color printing process
- Meeting automaker requirements (abrasion resistance, fogging, odor, emission, heat ageing, UV ageing….)

Several types of inks are known on the market: solvent-based inks, water-based inks, hot-melt inks, latex inks, UV curable inks, and so on. Our choice was to formulate solvent-based vinyl inks (Nakan® PrintSol) that offer the advantage of being fully compatible with PVC slush and which give a superior perceived quality especially for large printed areas in plain colors.

Concerning the ink formulation, the main parameters for good spitting from the inkjet head are:
- Rheology: Newtonian behavior
- Viscosity level
- Nozzle opening time (the time during which the head can be left inactive without jetting)
- Particle size distribution
- Surface tension.

The formulator must take into consideration the effect of each component on the overall performance of the ink. When the formulation is optimized, the ink forms droplets without satellites, thus ensuring a good quality of printing.

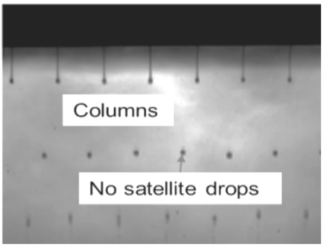


Fig 4: Jetting performance and drop formation

The formulation contains a vinyl polymer which is solubilized in different solvents, additives, thermal stabilizers, pigments and surfactants. The ink is dried by increasing the temperature in the heating oven before the slush molding process or by using an infrared lamp in post-printing. A film forms and achieves its optimum mechanical performance when the solvents have been completely evaporated.
The heat stabilizers ensure a good resistance to processing temperatures, and a complete transfer from the mold to the PVC skin without increasing the demolding force.

For this project, we have developed with our partners a specific 6-axis robotized digital printer able to print on curved surfaces. The robot uses a laser profilometer to scan the surface then selects the printing head with the right color, and prints the surface according to the design. The high-resolution printing head has 360 nozzles per inch spacing, for a total of 512 nozzles spitting 42 pl drops. Its compact design enables the head to print on concave areas, provided the radius of curvature is larger than 60 mm. The intrinsic path repeatability of the robot is approximately 100 µm. This accuracy is sufficient to ensure reliable printing on embossed / debossed areas.

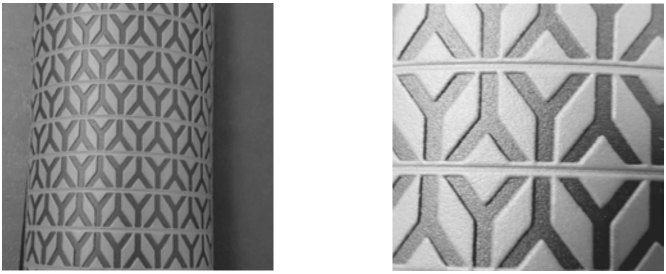


Fig 5: In-mold printed sample; embossed Y shapes are printed

The robot can pick a different printing head for multi-tone designs. The ink is color-matched according to the automaker’s requirement. The robotized digital printer can alternatively work in cyan, magenta, yellow, black and white colors (CMYK).

Another challenge was to meet abrasion resistance performance as specified in different OEM requirements. We have developed a specific varnish – inkjet-printable – composed of vinyl and acrylic resin that remains flexible and resistant to the slush molding process. In-mold printing, this varnish also makes it possible to control the wetting problems linked to variations in the surface tension of the substrate.

5 Results

Abrasion: very satisfactory results were achieved in the crockmeter test, with no significant transfer to white cotton cloth and a good aspect of the printed surface.

Fig 6: Crockmeter test, 100 cycles, black ink in-mold-printed, (DIN/EN/ISO 105-X 12 with additional weight of 10 N)

Other abrasion tests have been validated:

- Abrasion Taber : SAE J948
- Resistance to scuffing : SAE J365
- Resistance to cleaning agents : D235201

Print Quality: The use of a varnish before printing makes it possible to control the spreading of the ink at different temperatures. Printing on mold results in an impact diameter (DI) up to 200 µm at 40 °C while on varnish the spreading of the ink is limited to 90 µm whatever the temperature of the mold.

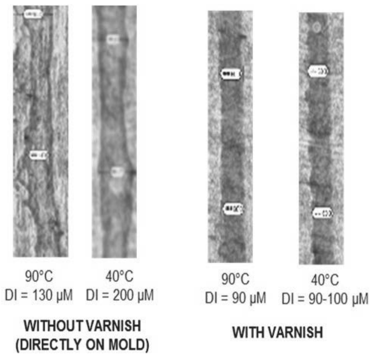


Fig 7: Spreading of the ink at different temperatures

Printing on a mold requires the surface tension of the substrate to be controlled before printing. In slush molding, the surface tension of the mold changes as a function of the number of skins produced; this modification results in a difference in the wetting of the ink evidenced by a change of the contact angle.

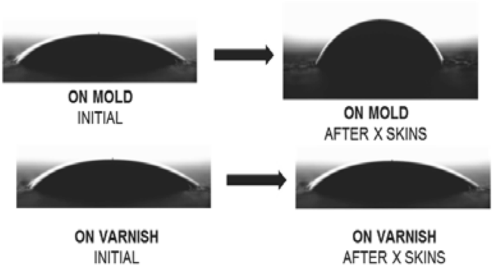


Fig 8: Ink wettability on mold and varnish

The use of a varnish permits the variations in the surface tension of the mold to be solved cycle after cycle during the slush molding process and thus makes it possible to ensure a consistent quality of printing.

The printing resolution is a key factor in ensuring a sharp design. A resolution of 360*360 dpi gives good results.

Fig 9: Printing with color-matched inks

Transfer temperature/demolding force: the ink was designed to be transferred from the mold to the skin, when using the in-mold-printing process, while maintaining a mold release force close to that of the standard slush powder.

	Commercial Ink (solvent-based)	Nakan®PrintSol
Transfer temperature	200 °C	230-235 °C
Transfer quality	Incomplete	Total
Demolding force	41 N	16 N

We evaluated the behavior of a solvent-based commercial ink in comparison with Nakan® PrintSol. The commercial ink does not withstand the high temperatures of the slush process, while our formulation contains thermal stabilizers and release agents to allow transfer up to a temperature of 230 °C while maintaining a release force of 16 N.

6 Technical comparison between in-mold- and post-printing

The instrument panel can be printed and customized using two processes which have their own advantages and drawbacks.

The ‘in-mold-printing process’ offers the highest perceived quality since the ink is totally integrated into the skin, and the grain remains identical in the printed and non-printed areas. This process thus ensures homogeneity of gloss. Furthermore, it is suitable for printing on embossed or debossed areas. Indeed, due to the consistency of the mold geometry for cycle after cycle, the scanner does not need to survey the surface before each printing. This process is not suitable for narrow molds such as door panel elements. The passenger area of the instrument panel can be printed easily with current printing head.

The ‘post-printing process’ offers an opportunity to customize a *standard part* at the very last moment, which is a real advantage in mass customization in shortening the response time. With this process a larger area of the instrument panel or door panel can be printed, and in favorable cases, edge to edge. However its main drawback relates to the grain, causing a levelling which increases the gloss. The other current limitation is the ability to print accurately on embossed or debossed areas, due to slight variations of geometry from part to part, thus making scanning of each part necessary before printing.

	In-mold-printing	Post-printing
Accessibility	Limited on edges and in narrow areas	Area of printing more important, edge to edge often possible
Robot installation	On the slush line	Offline
Impact on slush cycle time	Additional printing step	No effect as offline
Drying system	No additional step	Additional step on offline printing station
Printing quality on grain	Excellent, full respect of grain, no over-thickness, gloss homogeneity	Over-thickness causing a levelling of grain, increasing gloss locally
Printing on embossed or debossed areas	Feasibility validated, scanning of mold, not every part	More complex due to part to part variation, fast scanning of every part needed

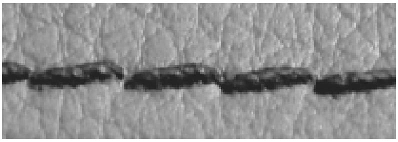


Fig 10: Faux stitches in-mold-printed

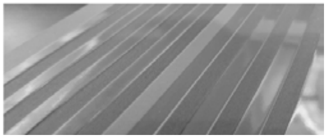


Fig 11: Lines embossed and debossed in-mold-printed

The development of vinyl inks and flexible robotized digital printing solution opens up the road to mass customization of instrument panels and other parts made by PVC slush.
This technology supports working with two different printing processes, either in-mold-printing or post-printing. In-mold-printing ensures a high perceived quality and a very precise positioning. The robotized printer is also able to print on final parts. This alternative post-printing process is useful for applying decoration in the very last step, although it has the inconvenience of being on top of the grain.

The next step for in-mold-printing is to work on accessibility using a smaller printing head. In post-printing, the challenge is to develop a rapid scanning technology for parts to ensure accurate positioning and to control the gloss of printed areas.

The IVY Group is collaborating with ABB to develop a ready-to-use robotized digital printing station. An illustration of an industrial post-printing station is shown below.

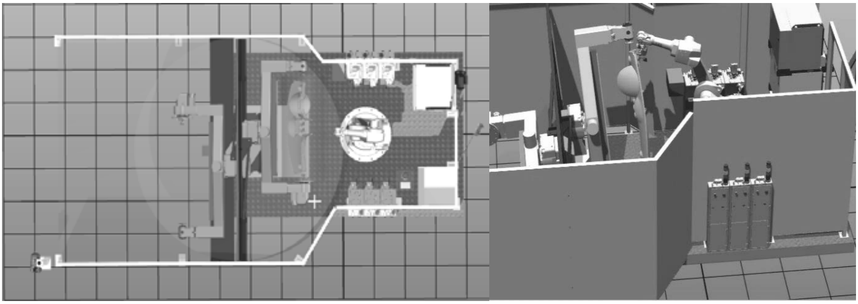


Fig 12: Design for a post-printing station

6 Acknowledgements

We would like to thank our partners for their involvement in this project, and especially Mr. Alain Maupas of ABB France.

7 References

[1] From Mass Marketing to Mass Customization, Phillip Kotler, Planning Review, September/October 1989

[2] Mass Customization, The New Frontier in Business Competition, B. Joseph Pine II, Harvard Business School Press, 1993

[3] How technology can drive the next wave of mass customization, Anshuk Gandhi, Carmen Mager and Roger Roberts, McKinsey on Business Technology, Number 32, Winter 2013

[4] Digital printing for flexible interior trim, Dr R. Tol, E Pinho et al., VDI Proceedings 2015

[5] Mass Customization and the Factory of the Future, Kevin O'Marah, SCM World

New surfaces and difficulties in applying existing test methods

Dipl.-Ing. **J. Guenther**, Dipl.-Ing. **D. Malecha**, J. **Reinicke**, B.Eng.,
Kunststoff-Institut Lüdenscheid, Lüdenscheid

Abstract

The first part of the paper deals in some detail with the technique of 'in-mold painting by flooding through PUR systems'. In the second part, a brief consideration is given of the complexity of the basic qualification and testing of new surfaces in the form of test methods for automotive OEMs, taking the example of the cross-hatch adhesion test.

Introduction

The most varied methods have long been used to refine plastic components. Refine in this context means to improve their actual appearance to help the components correspond to the various expectations of customers. The post facto modification of the component surface, and possibly even of its structure, can be effected by, for example, post-electroplating, PVD coatings, flocking or painting. It is important with many refinement processes that the untreated parts have no surface flaws since this would become visible later, after processing.

The second aspect of applying surface processes is the improvement in properties. The coating has the task of protecting the components against:

- Scratching
- Media, such as hand perspiration, creams, oils/fats, and so on
- Ultraviolet radiation.

The high quality appeal of the surface or components should thus be conserved even in the long term and sustainability throughout the product life cycle ensured.

1.1. 1.1 Painting

An example of this would be the painting of plastic parts in the automotive sector. In many cases, following the manufacturing process the components are transported to the service provider, where the components are to be painted. In this process the difficulty is particularly to be found in the aspect of 'cleanliness of the components', since surfaces could be contaminated during transportation of the moldings. It is important that the plastic parts have flawless surfaces because any damage to the surfaces can result in components being scrapped or in immense time delays and thus cost increases. Irrespective of which process is selected, later coatings generate additional costs, among other things due to the logistical effort. One significant advantage of painting inside the injection mold is the elimination of overspray. In a conventional painting process the excess paint must here be filtered with a great deal of effort in order to recycle it or it must be prepared for disposal. Since the paint system is injected into a closed mold during flooding, the paint cannot escape into the environment. In addition, coating the component by flooding inside the mold produces more brilliant surfaces with depth effects such as is seldom possible with traditional painting methods.

1.2 PUR: a versatile material

With in-mold painting there is the possibility of obtaining different thicknesses in the polyurethane coating process. Typical coatings have thicknesses between 200 µm and 1 mm. Surface defects of the plastic part can be thus in some cases be hidden, such as weld lines. Following a large number of trends, products with surface designs in piano black finish are increasingly popular and this can be very satisfactorily effected by flooding inside the mold. An additional high-quality level is thus achieved.

The properties of the systems used for this can be adjusted in various ways. For example, the coatings can have soft or hard surfaces. They can also be modified with regard to scratch or chemical resistance or equipped with self-healing effects. Both are possible in combination with the most diverse substrate materials, such as plastic – even backfoamed films – or wood.

In particular the exact reproduction of the surface makes new designs possible which traditional painting technology or other methods would not manage or only with a very great deal of effort.

In-mold painting now makes it possible to position matt surfaces in sharp contrast to high-gloss surfaces, to realize raised or recessed lettering, symbols or logos up to and including full-area structures and partial painting.

1.3 The process sequence of 'in-mold painting'

Painting or flooding the components requires a PUR installation, an injection-molding machine with a special interface and an injection mold with at least two cavities. The first stage is the traditional production of the molded component in the first cavity of the mold.

While the plastic molding or plastic carrier is being made, the two liquid streams circulate in separate circuits from the tank to the mixing head and back. Here the components are under high pressures of around 170 - 220 bar.
Firstly, a plastic part is produced conventionally by injection molding. It is then moved into a second, expanded cavity, which prescribes the coating thickness and surface structure. A slide table, turntable or cube mold can be used for this.
To enable thorough mixing of the materials (which have low viscosity in comparison with polymers), the two components, polyol and isocyanate, are mixed at high speed in opposing directions and then injected by a hydraulically operated control piston. At the end of the curing time required for the PUR system, the finished part can be demolded.

1.4 Areas of application for in-mold painting

One area of application for the PUR materials is the automotive sector. Polyurethanes are used here in different forms, such as, for example, foams, adhesives or paints. In the vehicle interior, trim strips made of different kinds of wood, center-console panels or plastic parts have already long been coated with polyurethane. They can be given special properties and functions by being coated with a tactile or optical layer of a PUR flooding paint. A tactile layer will give a different and entirely intended feel to a molding with a structured mostly thicker coating.
One example of this is a soft surface similar to leather. This is applied to various panels in the car interior.

Currently, transparent paint systems are mostly used which together with the basic color of the plastic or by in-mold laminating become a color system – for example, black components for the very piano-black look. What is interesting here is that surface defects are to a certain extent hidden, despite the transparency. Even colored PUR systems are basically possible. Here the PUR components can be pigmented but cleaning the machine for a change of color is so troublesome that this technique is rarely used in practice. It is also possible to inject the coloring directly at the mixing head via a third or, if necessary, a fourth component. This is a much more attractive but, as regards the investment required, also a more expensive solution.

When the investment costs and space requirements for a new installation are compared, the PUR method comes out a clear winner over painting.

With regard to the ecological use of raw materials and a usual overspray of up to 80% with the painting technique, the PUR method in the best case can here too expect a utilization ratio of almost 100%.
The self-healing properties of PUR systems with regard to fine scratches makes the systems additionally attractive from the customer's point of view and is supportive of sustainability.

1.5 The mold

Various solutions are available for moving the plastic component as quickly and as efficiently as possible into a second and larger cavity. Care should be taken even at the start of the planning stage as to which type of mold makes most sense and seems most cost-effective for the molding. The possibilities offered by a sliding-table, insert, or cube mold or an adapted turntable are designed for different batch sizes. Specific solutions are available from various companies specializing in PUR mold-making.
Unlike thermoplastics, polyurethane is a material with an extremely low viscosity. This means that the mold designer must in particular ensure adequate but not excessive venting. In the latter case the low-viscosity polyurethane could get into the mold parting line and the venting channels. This may result in similar defects to such as occur with thermoplastic parts (flash). The complexity of a PUR mold is similar to the complexity of the molds used in processing silicon and calls for specialist mold-making.
Since the usual high-speed mixing heads require a minimum dispensing volume, attention should also be paid to the size of the cavity. If the component size or number of cavities cannot guarantee a sufficiently high shot volume, it will be necessary to work with a corresponding overflow cavity.

1.6 Release agents

Release agents are essential in polyurethane processing, either of the internal or external type, since otherwise massive adhesions and deposits would result in the mold. Release agents are therefore used which prevent the polyurethane sticking to the mold wall. These form a closed barrier between the PUR and the mold wall. As mentioned earlier, release agents may be divided into internal release agents contained for the most part in the polyol component and external release agents applied to the mold surface by spray gun or brush. However, in some cases using internal release agents is insufficient and external release agents need to be used as well or even primarily. These range from sprays, which form a thin layer between the mold wall and the PUR layer, to mold coatings. However they are good for only a limited albeit comparatively high number of pieces. The demands made of

PUR release agents are high, which makes it difficulty to design PUR systems suitable for series production. On the one hand, the effect of the release agent should be as reliable as it is effective, while on the other the PUR layers should be able to adhere well to the substrate. The manufacturer and processor must find a compromise here in which the release agent does not interfere with adhesion to the substrate but where sufficient adhesion of the coating can be guaranteed. In addition, the release agent should have no influence on the resistance of the paint to media or test substances.

1.7 Cycle time

Since polyurethane coatings are reactive casting resins they need some time to cure fully. Curing times of approx. 30-150 seconds have been measured in various tests and are quoted by manufacturers. The resulting cycle times in combination with different plastics range from about 70-190 seconds. Paint system manufacturers are striving to secure a continuous reduction in curing times. The reaction rate, however, should be adapted to the limiting parameters of the machine and not exceed or fall short of these.

1.8 Painting or in-mold painting

If the moldings produced are to be subsequently painted, their surfaces must be flawless – that is, smooth and clean – if a perfect paint job is to be possible. Failure to pretreat the surface and clear it of irregularities and contamination will result in the painting process subsequently reproducing these flaws. Where there were points of contamination, so too will they also be found after spray painting. In contrast, with PUR painting the surface will not be contaminated during transportation or relocation. Furthermore, an uneven rough surface can be smoothed over with the clear embedding compound since the quality of the PUR surface is predetermined by the surface roughness, structure and dimensions of the mold wall or mold.

1.9 Further investigations

The Kunststoff-Institut Lüdenscheid, as part of the inter-company project 'Surface treatment of plastic moldings', with more than 30 participating project partners, is addressing among other things the subject of in-mold painting. Since 2014, the basic principles of this technology have been worked out within the project, test pieces made from different combinations of materials (plastic/paint system), and selected automotive tests used to check the performance of the components thus produced. In the current project period, anti-adhesive tool coatings should be identified which would if possible eliminate the use of release agents.

Furthermore, the possibilities of structure reproduction in the injection mold are being investigated and cost-effectiveness investigated on the test stand in comparison with conventional painting.

2. Qualification / test technology

The automotive industry makes special demands of a coated plastic surface. As part of the qualification process, various test methods are applied to check scratch and abrasion resistance, resistance to chemical attack, climatic resistance, resistance to weathering, and also biocompatibility (emissions). Coated plastic surfaces are also subjected to adhesion tests.

In general, the properties and the qualification of a surface can be described by four main factors: visual appearance, the function of a surface, tactile properties, and resistance to external influences (Fig. 1).

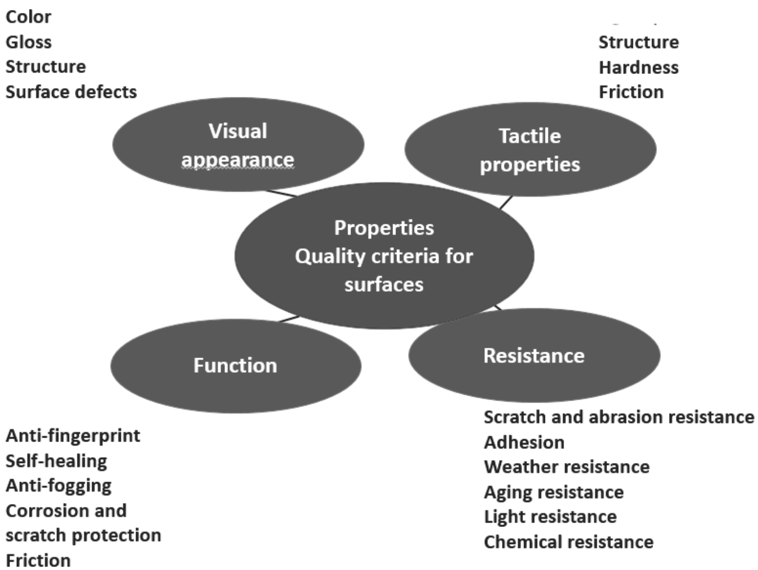


Fig. 1: Quality criteria for surfaces

In addition, the aesthetic demands of customers must also be satisfied. This results in the requirement to check tactile properties, the constancy and the preservation of hue and glossiness, and also visual appearance as a whole, using standardized methods which, if at all possible, supply reproducible and comparable results. The wide range of possibilities and also the type of stress and also the type of assessment are reflected in the abundance and diversity of the established test procedures.

2.1 Test standards

DIN EN ISO standards in many cases only specify the general conditions under which a particular test is to be applied, leaving a great deal of latitude. Automotive standards often include more details regarding the test effort. Every manufacturer has its factory standards catalog, in which the article qualification tests binding on the OEM are laid out. Special requirements applicable to components in the automotive sector are covered by customized test specifications. Some automotive standards are based on DIN (EN, ISO) standards, some were jointly prepared under the VDA umbrella, while others have been developed completely independently. Examples of works standards for painted plastic parts are VW standard TL 226 (TL = technical specifications) and Daimler-Benz standard DBL 7384 (DBL = Daimler-Benz technical specifications).

The example of the VW standard clearly shows the extent to which surface inspections can be implemented (Fig. 2).

TL 226 VW AG						
Test	Standard	Evaluation		Test	Standard	Evaluation
Color and gloss	VW50190	Initial sample inspection		Lightfastness	PV1303 Conditions depending on the position of the component	No change among other things according to the gray scale Adhesion and scratch test
Outdoor weathering	VW50185	Paint system		Hydolysis strorage	Heat and very high humidity 40 °C // ≥ 96% RH	No change in color and feel Adhesion and scratch test
Adhesion	Cross-hatch DIN EN ISO 2409 Requirement: Gt ≤ 1	Alternative cross-cut Requirement: no adherent paint particles		Sunlight simulation	DIN 75220	No change in color and feel Adhesion and scratch test
Scratch resistance	PV 3952 Requirement: no rupturing of the paint	Alternatively, Erichsen hardness Requirement: no rupturing of the paint		Dry abrasion Damp abrasion Abrasion against cleaning agents	PV 3906; crockmeter	No change in the surface; the abrasion fabric used gray scale GM ≥ 4
Heat storage	Circulating-air heat cabinet Conditions depending on the position of the component	No change in the look and feel; adhesion and scratch test		Resistance to cleaning agents and synthetic perspiration	Dripping test	No change in paint color, gloss or paint structure
Alternating climate test	PV 1200, PV 2005	No change in the look and feel; adhesion and scratch test		Cream resistance	PV 3964	No changes in color or feel; gloss increase is allowed; adhesion and scratch test
Condensation constant climate	Implementation: DIN EN ISO 6270-2	Assessment of blistering; adhesion and scratch test		Abrasion resistance for high-gloss surfaces	PV 3975 (for Volkswagen)	Residual gloss

Fig. 2: Brief summary of the possible scope of inspection and assessment in the example of VW TL 226

Implementation of an OEM standard is here to be regarded as anything but trivial and transparent. There are many cross-references between standards and test methods must be combined and time-coordinated. Which test should be applied in each case or which test result is considered as passed, depends on the material, the component itself, the position in the vehicle and the load situation. In addition, the applicability of tests depends on the component size and geometry, so that either the test must be modified (for example, saltire cross instead of crosshatch) or test plates will have to be used whose comparability with the original components is only to be regarded as limited.

One particular hurdle is that not every company is permitted to carry out every test itself. Accordingly, there are requirements, depending on the OEMs, concerning the accreditization of laboratories to ISO 17025 – which is again required in company certification in accordance with TS 16949 – up to and including special approvals for special tests, such as participation in a special ring trial or even an OEM-specific certification. Unfortunately the specifications do not usually themselves specify which qualification is required but rather separate documents, which, like the standards, are subject to continual changes.

2.2 'Simple' tests

Seemingly simple tests such as the cross-hatch test are supposed to make it possible to assess surface quality rapidly before and after stresses.

Before proceeding it is important, despite simple handling in the test, for components to be pre-conditioned to ensure that paint systems, for example, have also completely cured. In the examples of VW and Daimler there are various differences in the specifications regarding pre-conditioning. Before a test, both automakers provide for fast conditioning in the form of 48 h heat ageing at 60 °C. Some manufacturers specify 7 days conditioning at room temperature as an option or mandatorily. This is to ensure that after painting all solvents have evaporated and the final properties of the system have been reached.

The surface under test is usually cleaned before an adhesion test. A mixture of isopropanol and water (ratio 1: 1) is suitable for this purpose but also cleaning agents (surfactants). The use of more aggressive cleaning agents is not recommended: invisible surface defects such as microcracks may arise. Cross-hatch cutting may be carried out next. Here the number of cuts, the average spacing and the blade geometry may vary. Should the shape of the part make it impossible to carry out cross-hatch cutting, a so-called saltire or cross-cut should be applied. The cross is cut down into the substrate with a sharp, thin blade (for example, a safety knife with a trapezoidal blade). The small acute angles of the saltire cross are particularly sensitive to tearing open of the coating. After removal of excess material with a brush, a defined Tesa fabric tape is applied and abruptly torn away.

A classification into cross-hatch classes can be used for evaluating the damage pattern produced (Figure 3). Here not only the coated surface should be considered but also the peeled-off Tesa fabric tape.

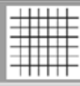
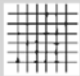
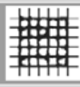
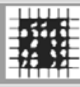
Cross-hatch adhesion class	Description-	Appearance of the surface in the vicinity of the cross-hatch cut at which detachment has occurred (example of six parallel cuts)
0	The edges of the cut are completely smooth; none of the squares in the grid has detached.	
1	Small flakes of the coating have detached at the grid line intersections Detached area not greater than 5% of the cross-hatch area.	
2	The coating has detached along the cut edges and / or at the intersections of the grid lines. Detached area greater than 5% but not greater than 15% of the cross-hatch area	
3	The coating has partially or entirely detached along the cut edges in broad strips and/or some squares have partially or entirely detached. Detached area greater than 15% but not greater than 35% of the cross-hatch area.	
4	The coating has detached along the cut edges in broad strips and/or some squares have partially or entirely detached. Detached area greater than 35% but not greater than 65% of the cross-hatch area.	
5	Any detachment which can no longer be classified as cross-hatch adhesion class 4	---

Fig**.** 3: Cross-hatch adhesion classes according to DIN ISO 2409 [1]

As a rule, the only results which can be accepted are cross-hatch adhesion class 1 and better. Poorer results must be reviewed, if necessary, these results must be also communicated to the OEM.

Depending on the OEM specification and the component not only multiple blade devices are permitted but also cutter blades. However these often have different shapes and thus also make different cuts.

Although many constraints of the tests are clearly defined, it is a test that depends heavily on the approach of the individual inspectors:

- Test force
- Continuity of the cutting operation
- Parallelism / squareness of cuts
- Adhesive strength of the adhesive tape
- Application and tearing off of the adhesive tape (force, speed, angle)
- Interpretation of the resulting pattern.

Another important aspect must also be mentioned: the cross-hatch adhesion test must be carried out such that the coating is only just fully penetrated and the surface of the component is exposed.

This means that it is not permissible, as is often the case in practice, to cut down deep into the substrate with 'maximum force' as otherwise non-comparable results would be expected.

With regard to the consideration of different coatings, it should also be mentioned that the edges of cuts tend to be smooth in the case of soft-touch paints (GT 0) unlike with glassy, brittle, scratch-resistant UV MonoCure paints (GT 1). It would be a false conclusion to deduce from this that soft-touch paints basically have better adherence properties than UV paints.

Neither should the influence of humidity be underestimated, nor that of component cleaning which changes sliding friction/effect properties. In the case of the cross-hatch adhesion test, this effect is to be less expected subjectively, but with other tests, such as those with the Erichsen rod, serious changes in results were found during investigations at the Kunststoff-Institut Lüdenscheid – and in most specifications standard climate is prescribed when carrying out the Erichsen test.

On the basis of these simple examples, which could be multiplied indefinitely, the recommendation must be made that in the presence of divergent results or even with an unexplained or sporadic failure to pass tests, experts should first precisely check test conditions instead of first of all questioning and changing the coating process and the suitability of the material.

2.3 New processes / materials

One special challenge a company faces is when it has developed a new material or would like to use a new system and wishes to qualify it for different OEMs, such as is the case with in-mold painting.

The OEM frequently then asks the legitimate question: 'Have you already passed the X test?' Full qualification to an OEM specification is however to be regarded as time-consuming and expensive – in many cases 2-4 weeks is required for the weathering test alone and external costs of more than €10K are incurred per OEM and system!

Furthermore, the complete test specification must be checked again as soon as changes are made to the system under test. If no special arrangements have been made, it may therefore in the extreme case mean a new system already failing the cross-hatch test in the unloaded state but the full specification being checked. After this the material has to be changed and costs rise once again.

KIMW Prüf- und Analyse GmbH has developed a special system for reducing the expense and minimizing the risk to the company of this kind of problem. To this end a grid (not for sale) was created in which the specifications of a series of automotive OEMS were listed and systematized.

Groups were formed in the area of basic types of stress and an individual testing systematic can now be offered which covers all categories and, depending on customer requirements, shows:

- the shortest testing time
- subjectively the most critical individual tests
- the broadest possible mix of different OEMs.

Here, of course, individual categories can initially be omitted (for example, weathering, emission tests). A useful order and halting points at failure to pass individual tests can be agreed on individually.

Although this does not free the vendors of new systems from qualifying their system for final approval with an OEM, but they do first obtain proof of the performance of their system in the form of an independent test report from an accredited laboratory with which they can first 'audition' at various OEMs. This should create greater confidence in the OEM and minimize risks, costs and time expense at the vendor.

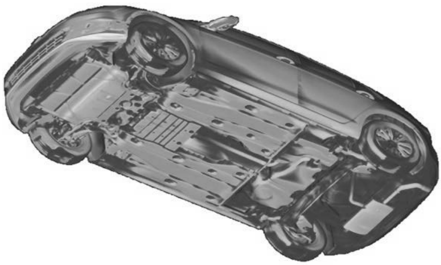
[1] DIN EN ISO standard Paints and varnishes - Cross-cut test (ISO 2409:2013); German version EN ISO 2409:2013

The underbody: an underestimated contribution to CO_2 reduction

O. Mende, Volkswagen AG, Wolfsburg

Abstract

The aerodynamics and lightweight design of motor vehicles will greatly gain in importance due to future CO_2 legislation. This paper describes potential in the area of vehicle underbody and how requirements can be implemented by means of a material module. How the best design can be obtained for the vehicle underbody in the arena where aerodynamics, costs and lightweighting contend is also described, as well as the challenges involved.

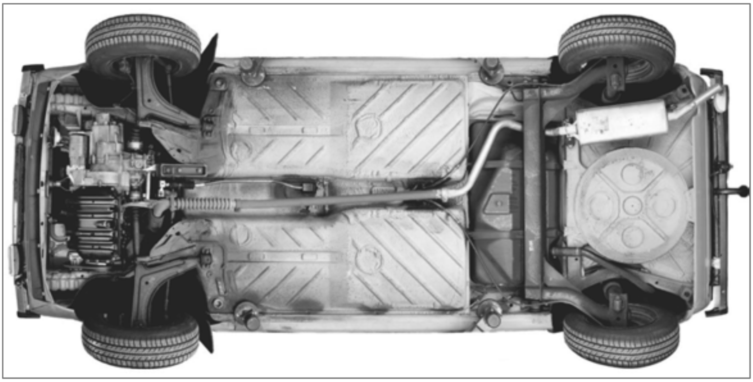


1. History of the underbody in the example of the Volkswagen Golf

1 Golf 1 to Golf 7

When the first Golf came off the production line in 1974 no special demands were being made of the properties of the underbody as regards CO_2 emissions. Neither aerodynamics nor lightweighting had any direct impact on development. The engine and other assemblies were exposed, the mid-underbody area was shielded solely by PVC to protect it against corrosion.

With a drag coefficient (c_w value) above 0.4, which was still in keeping with the period, the Golf 1 had a relatively high air resistance when compared with today's vehicles. However, due to lower safety and comfort requirements, it was very much lighter than is usual today.



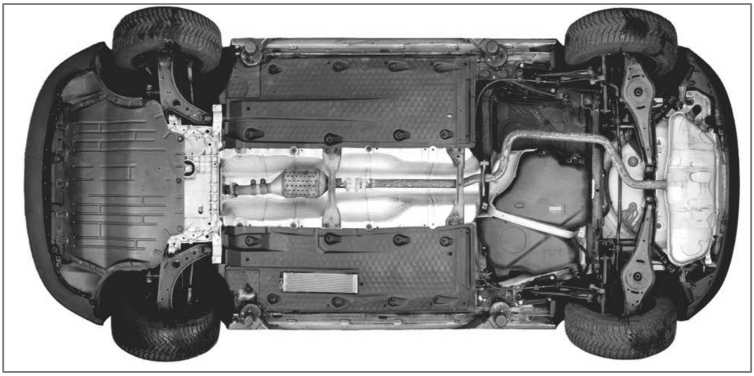
2 Golf 1 underbody

Due to changing constraints and constantly increasing crude oil prices, in the development of the Golf 2 importance was attached to improved aerodynamics. The average drag coefficient value of 0.35 shows that significant efforts were already being made to meet the stricter requirements.
However, the focus of optimization work was limited to the body alone. Possible areas of potential in the underbody remained as yet unexploited. This was also the case with the Golf 3.

The first optimizations were achieved with the development of the Golf 4, which was based on the PQ34 platform and was introduced onto the market in 1997. In the area of the engine and other assemblies, enclosures were used to protect the components from environmental influences. This resulted in a positive side-effect: for the first time the aerodynamics in the underbody were improved. Depending on the environment and different interactions, the influence of the engine shielding capsule can bring about an improvement in the drag coefficient of up to 0.007.

The PQ35 platform is in production today in China and has frequently been aerodynamically optimized by additional components.

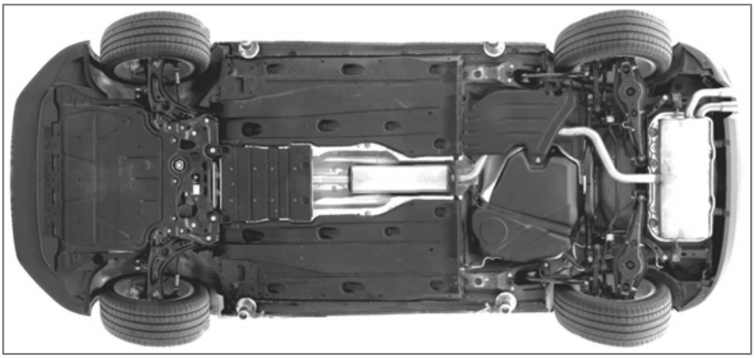
The Golf 5 and Golf 6, both technically based on the PQ35 platform, then show a much better picture. They have large panels in the mid-underbody area and a relatively smooth surface as far back as the fuel tank.



3 Underbody of the Golf 5 and Golf 6 (PQ35)

Volkswagen used the modular transverse matrix (MQB) for the first time in the Golf 7. Already visible here are optimizations regarding not only aerodynamic properties but also weight, resulting from individualized material selection.

MQB components are used in their millions across all brands and classes. For example, the engine capsule is used not only in the Golf but also in the Touran and Passat and even in the Audi A3 and Skoda Superb, for example. Vehicle-specific requirements must already be taken into consideration in the early development phase to enable installation across the board.

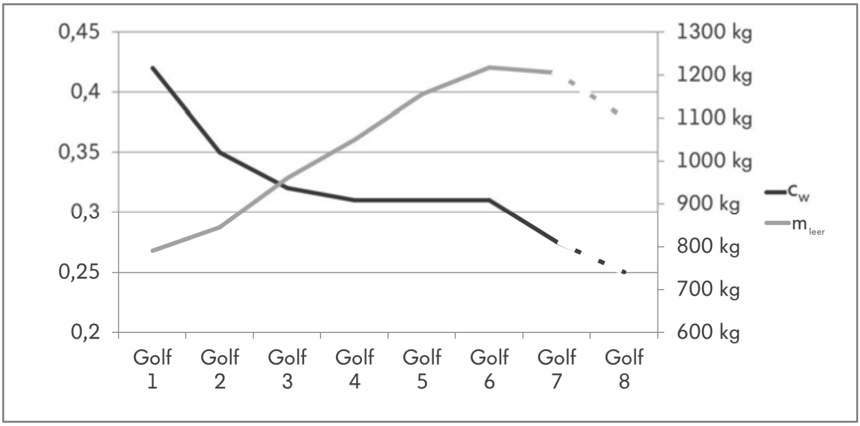


4 Underbody of the Golf 7 (MQB)

Due to constantly increasing demands with regard to CO_2 emissions, it is necessary to cover over ever greater areas of the underbody. In the case of the Touran and Passat, only some relatively small areas are left uncovered today.

Up until the Golf 6, the lower curb weight increased significantly with each generation. The drag coefficient stagnated for many years. Lower values reappeared with the Golf 7.

For new developments in the future it appears essential to take advantage of any potential in the underbody. Average drag coefficient values below 0.25 are required in the compact class in order to survive in the competition and to comply with future legislation.

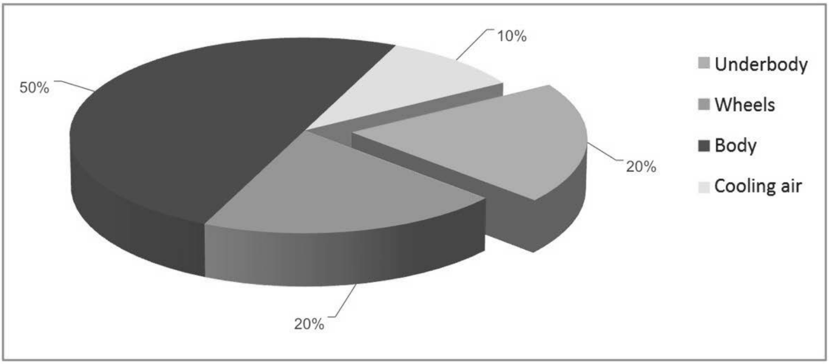


5 Weight and drag coefficient curves

2. Influence of the underbody on a vehicle's CO_2 emissions

In attempting to determine the contributors to the drag coefficient it becomes clear that the vehicle body makes the biggest contribution, at around 50%. Wheels and cooling air contribute about 30%.

The underbody is estimated, depending on the limits set, to contribute about 20%. In the case of a compact-class car, with a mean drag coefficient value of 0.3 still typical of today, this means a contribution of 0.06 or 60/1000.



6 Distribution of air resistance in a typical compact-class car

Studies show that a large proportion of it can be reduced if the combination of body, cooling air intake and outlet, and underbody design is optimally utilized. For example, improvements can be achieved if the cooling air flows out specifically in a particular area of the transmission tunnel.

It is known from motor racing that aerodynamically optimized underbodies have a huge influence on driving characteristics. For example, so-called diffusers, such as are found in racing cars, if designed skillfully can not only increase downforce but can also reduce air resistance.

With the XL1, Volkswagen has demonstrated what can be achieved with an optimal design. With a drag coefficient of 0.186 it currently leads the field for production vehicles.

In 2020 a more stringent limit value for CO_2 emissions from vehicles will come into force in the EU. Here the entire fleet of a manufacturer will be subject to the emission limit of only 95 g CO_2/km in the New European Driving Cycle (NEDC). Further stringent requirements have already been announced in other markets as well.

In the EU, violation of the limit value means severe fines of €95 per gram and vehicle. If, for example, a manufacturer sells one million vehicles and on average exceeds the limit by 1 g CO_2/km, the fine would be €95 million.

In a typical compact-class vehicle with a diesel engine the following equivalents roughly apply in the NEDC:

$$\mathbf{1\ g\ CO_2\,/\,km \triangleq 0.015\ c_w \triangleq 30\ kg \triangleq 0.04\ l\,/\,100\ km}$$

In other words, a c_w improvement of 0.015 will reduce the CO_2 emissions of the vehicle by about 1 gram. The same applies to a weight reduction of 30 kg.
Assuming that a vehicle has a lifespan of 250,000 km, the improvements mentioned will save 100 liters of diesel fuel in the NEDC cycle. In the real situation, consumption will be correspondingly higher.

If a particular vehicle is found to be close to violating the CO_2 limit, it may make economic sense to undertake improvement measures under the constraints mentioned above.

Solving the above equation and relating it to the fines yields the following equation within narrow limits:

$$\mathbf{0.001\ c_w \triangleq 2\ kg \triangleq €6}$$

This means that it can be worthwhile to invest up to €6 per vehicle for an improvement of 0.001 in the drag coefficient or a weight reduction of 2 kg.

A typical optimization of the drag coefficient in the underbody will lie between 0.002 and 0.007, which makes it worthwhile within these limits to implement almost any measure if this means being able to avoid a corresponding fine. When the worldwide harmonized light vehicles test procedure (WLTP) is introduced gradually from 2017 onwards, the influence of aerodynamics due to higher speeds in the driving profile will again increase by around 50%.

But it is necessary to optimize the underbody, and not solely for legislation-related reasons. The customer expects his new vehicle not only to be safer and more comfortable but above all also to consume less fuel. The means that every new vehicle development must achieve an optimum in costs, weight, robustness, aerodynamics and so on.

If CO_2 legislation with regard to the fleet consumption of a manufacturer is gradually to be made even more restrictive in the future, compliance with this requirement will then only possible by having a large proportion of electrified vehicles. Electric vehicles are currently assessed as having emissions of 0 g CO_2/km but here too well-designed underbody panels will have a positive effect on aerodynamics and weight.
Range is currently one of the biggest areas of criticism of these vehicles. Since battery cells are at the present time the main cost driver it is even more worthwhile here than is the case with conventional drives to apply the measures described in this contribution to increase range or reduce battery capacity.

3. Development of a material matrix for the selective optimization of the underbody

Depending on the requirements made of the individual component in the underbody, there are various materials which have been optimized to their particular purpose. There is no material which functions optimally in every location for every intended purpose.

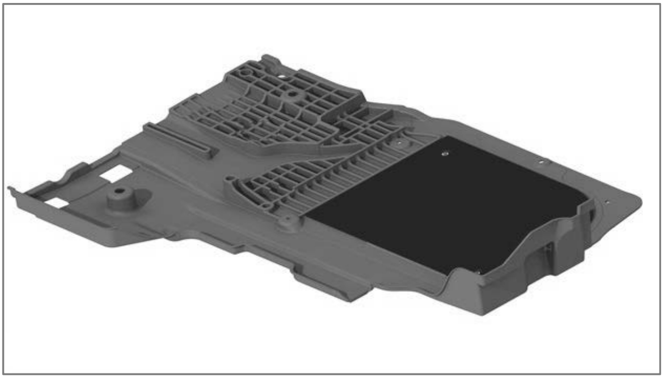
Depending on the requirements of the vehicle, there are a number of potential semi-finished products which are available for selection. The focus is on the following criteria here:

a) Robustness

In the case of the Golf 7 GTE plug-in hybrid, it became clear during the course of development work that the sensitive HV battery in the underbody meant that additional protective measures would be necessary. The housing of the battery is made of cast aluminum alloy 3.5 mm thick.

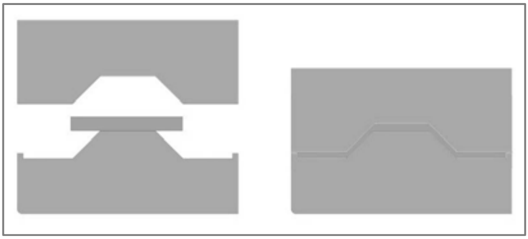
Full compliance with the requirements of various tests under everyday operating conditions meant that a panel was needed that had to be stronger than a straightforward polypropylene compound.

As a solution, a polypropylene with 50% glass fiber and a wall thickness of 5 mm was selected, and reinforced with a solid ribbed structure. In the area with the highest loading, a glass-fiber fabric was incorporated to provide additional robustness.



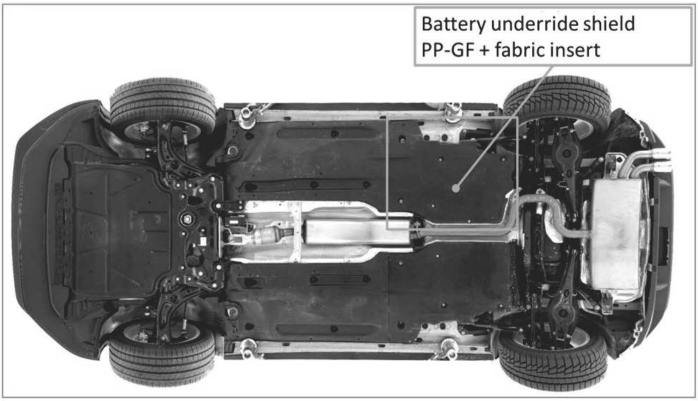
7 Battery underride protection in the Golf GTE

This component is manufactured by the thermal flow molding process in which the prepreg is massively reshaped in a similar way to forging.



8 The thermal flow molding process

On each side the so-called battery underride shield weighs about 5 kg. A comparable steel component would weigh over 10 kg and additional corrosion protection measures would be required.



9 Underbody of the Golf GTE (MQB PHEV)

Compared with injection molding, the thermal flow molding process has the advantage of significantly longer fibers (approximately 10 mm instead of less than 1 mm). The term LFT (long-fiber thermoplastics) is also used here.

In the case of MQB this process is also used in the production of the engine shielding capsule. It is, however, only 2 mm thick and no additional glass fabric is used.

Here too LFT is used in order to advantage of the greater rigidity compared with conventional injection molding.

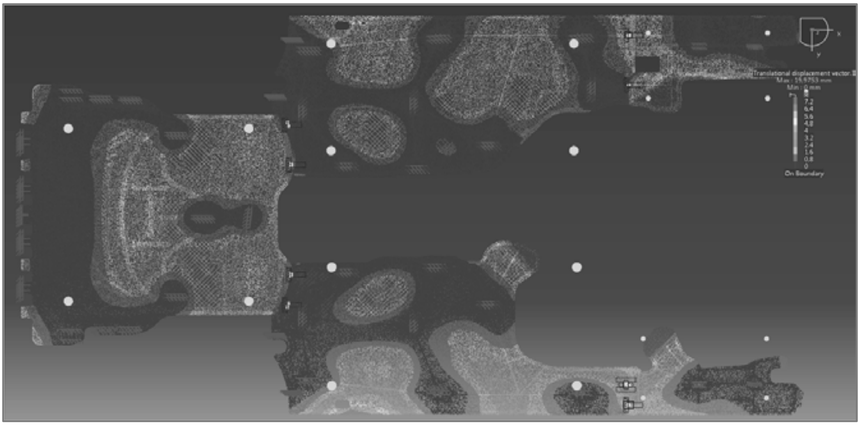
b) Lightweighting

Regular polypropylene with filler material has a density of approx. 1.1 kg/dm^3. With an average material thickness of 1.8 mm, this gives a weight per unit area of **2** kg/m^2.

If an LWRT (lightweight reinforced thermoplastic) is used, a weight reduction of up to 50% can be achieved. However this will be at around 250% of the cost of an injection-molded part.

To achieve the same weight advantages without having to accept the full additional costs, Volkswagen is the first OEM worldwide to use a lightweight GMT (glass mat thermoplastic), and this is used in the 2015 Touran. In its production this differs from conventional methods. A multi-layered polypropylene with needled glass fibers is placed in a compression mold and then trimmed by the water-jet cutting technique.
The method is very similar to deep-drawing without clamping devices in sheet-metal parts manufacturing.
In the Touran this material is used for the mid-underbody panels. Compared with conventional injection molding this saves more than 1.5 kg weight per vehicle with moderate additional costs.

If modern lightweight plastics have to be ruled out for reasons of cost, lightweight construction will still not be impossible. What a few years ago was still new territory in underbody development has now firmly established itself in the development process: that is, the use of the finite element method (FEM). This makes it possible to optimize the components specifically with regard to wall thicknesses and connection points. By constantly making practical adjustments Volkswagen today is in a position to make very accurate predictions and thereby not only to develop lighter components but also to save on development loops. Here the FEM interface in CATIA V5 has proved its worth and is easy for designers to apply.

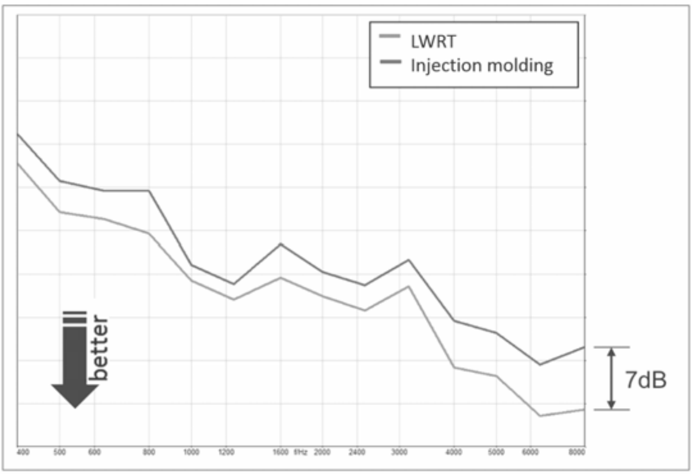


10 FEM simulation of a set of underbody panels

c) Acoustics

If acoustic properties are required in addition to the lightweight design – for higher vehicle classes, for example – an LWRT can be used. Production is very similar to the lightweight GMT. However, preparation of the prepreg is more complex. Depending on the supplier, polypropylene and glass fibers are mixed together and needled, after which they are glued to a sturdy PET surfacing mat.
During component production the fibers line up and the component is baked by this (lofted). Permeability leads to improved acoustic properties. The use of LWRT has now become established from the B class upwards since in these vehicle classes customers make particularly high demands of the acoustics and are also willing to bear the additional costs.

In the case of Passat models since 2014 LWRT is used in various equipment options. This reduces the external noise perceptible in the vehicle interior by up to 7 dB, which is clearly noticeable for the passengers. The use of LWRT saves more than 2.5 kg in comparison with the conventional equipment.

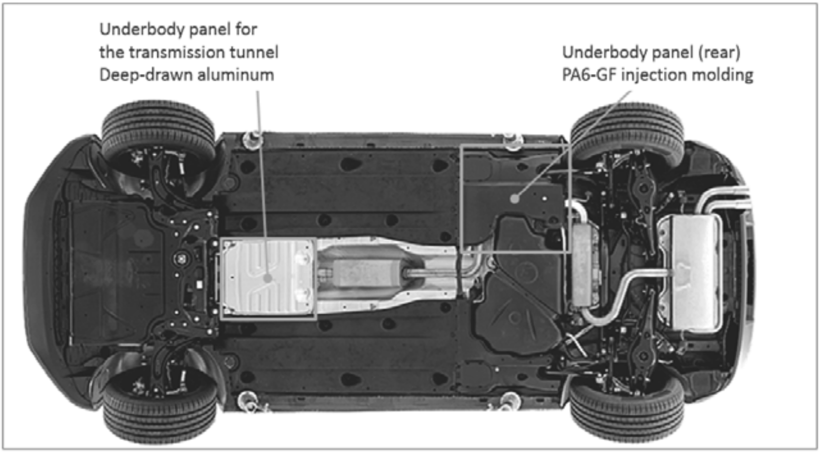


11 Sound transmission measurement on the test rig

d) Temperature resistance

In many places in the vehicle the materials we have described cannot withstand the high operating temperatures. In many areas of the exhaust system, temperatures run into several hundreds of degrees °C. In the Golf 1 adequate throughflow of air and cooling was achieved by the underbody being completely open. In modern vehicles the front end is covered to the point that hot air builds up further back and temperatures thus occur which are well above the permissible limits for polypropylene.

There are various approaches to solving this problem. In the area of the exhaust catalytic converter it becomes so hot that every standard plastic fails. For this reason Volkswagen employs for the first time a deep-drawn aluminum alloy in the Touran. Rigorous use of FEM even made it possible to make a weight saving over the foil-laminated plastic component used in the Golf.



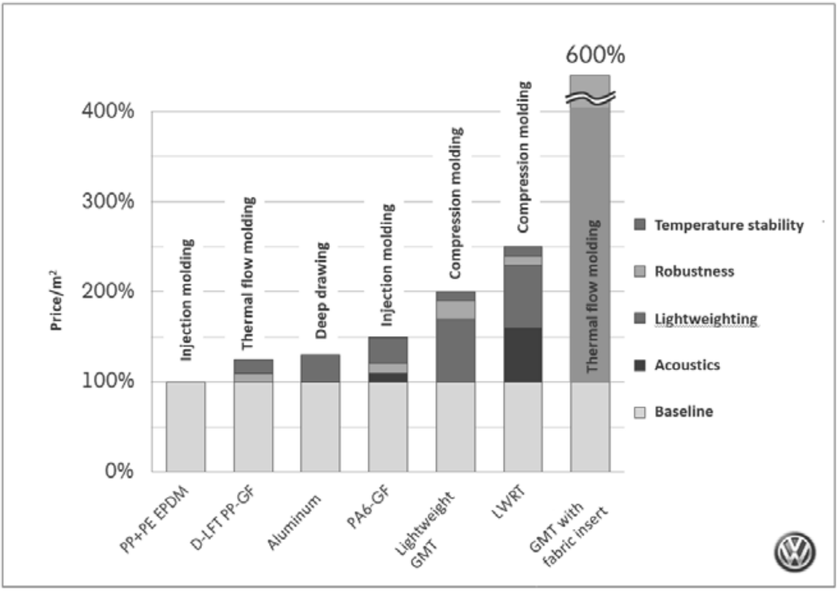
12 Underbody of the Touran MJ 2015

In the rear area of the Touran the exhaust system should be covered as a measure to reduce the drag coefficient. Aluminum had to be ruled out for acoustic reasons (stone impact). An impact-strength-optimized polyamide (PA) has been selected here which has a much better temperature resistance than PP. A positive side effect is that PA is also considerably more rigid. Although the area covered is large this rigidity means that only a few connection points are needed.

Cost drivers

Depending on which properties are required, a whole toolbox of materials is available to the developer.

The graph shows how the properties affect the cost. Costs per m² of covered area are shown. Also input into the graph are typical material thicknesses and reinforcements. A GMT with glass fabric is so expensive because among other things it has to be comparatively thick, at up to 5 mm, to give a high level of robustness. In comparison, lightweight GMT designs are typically only 1.1 mm thick.

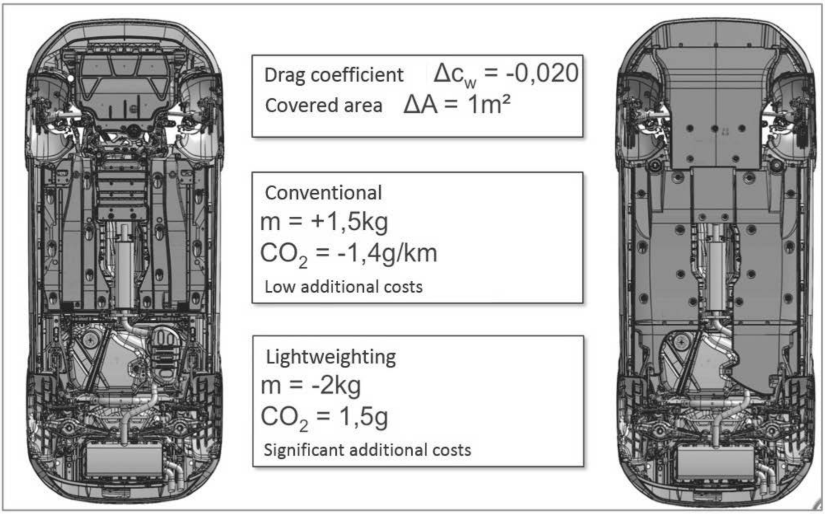


13 Comparison of cost drivers

Outlook

As has been described in the previous sections, many factors are involved in the development of the underbody. What is certain is that the requirements described will keep on increasing, in particular with regard to CO_2, range and fuel consumption, thereby making it essential to exploit every known area of potential.

Preliminary developments for optimizing components are continually in progress to make Volkswagen fit for the future. Within this framework it has emerged that further improvements in aerodynamics and weight are possible even with relatively little effort and minor modifications.
It seems realistic to achieve an aerodynamic improvement of up to 0.02 in the drag coefficient at little extra cost and without a significant weight increase.



14 Optimized underbody of the Golf 7

If lightweighting and acoustics are also to make their contribution, the use of lightweight GMT and/or LWRT can even result in a weight reduction despite the larger covered area.

If the assumptions made in Section 2 are taken into consideration, these optimizations will result in up to 150 liters less fuel being consumed over the vehicle's lifetime.

4. Conclusion

In the next few years no vehicle manufacturer will be able to afford ignoring the potentials in the vehicle underbody which have been described in this paper. In other words, it is not a question of whether the underbody is covered but rather only of how. As regards finding an optimum balance in the conflict field of cost, weight, drag coefficient and so on, Volkswagen is well prepared for the future.

Bumper in thin-wall technology: an update regarding materials, processes, and technology innovations

Dipl.-Ing. **J. Götzelmann**, Magna Exteriors, Sailauf;
Dipl.-Ing. **P. Diehl**, Magna Exteriors, Esslingen

Abstract

There has been continuous further development in the integration of functions and thus the demands made of bumper fascias. From an independent system for preventing minor damage they have grown into a form-integrated styling element with expanded demands made of aerodynamics, passive safety and sensors. This has also meant that the number of components to be integrated has steadily increased. System weight has risen significantly, especially in the case of so-called 'soft nose' models which have taken over parts of the bonnet and fenders. The present contribution deals with the subject of how worthwhile weight reductions can be achieved through the wall thickness reductions made possible by new, improved types of polypropylene (PP) with greater flowability and stiffness. Paint specifications and the quality requirements of a Class A surface must, of course, be satisfied with no compromises. Accordingly, the applicability of new developments in ultrasonic welding to series production was specifically investigated and further development work carried out until series production readiness.

Introduction

1. Holistic requirements management for bumper fascias

First of all, the product specification requirements of the OEMs must naturally be met. Essentially these cover requirements relating to completion of the component's service life on the vehicle. This criterion is deemed satisfied when deformations of the bumper fascia in climatic and vibration tests have been reduced to an acceptable level. Other product specification requirements include resistance to climatic conditions and weathering, energy absorption, and the contribution of the bumper fascia to active and passive pedestrian safety.

In addition to this, the quality standards of our customers are also becoming ever more demanding. System suppliers face ever greater challenges in complying with the tightest tolerances and narrow limits in joints and gaps. In the exterior styling, the design language goes further in the direction of a high-quality look which manifests itself in the tightest radii and large, relatively flat free-form surfaces.

In contrast, processes manageable to a high quality level are required of suppliers. The focus here is on injection-molding technology with straightforward processing of materials and on application technology with process-reliable painting and welding methods.

In addition, system suppliers are required by the vehicle manufacturer to make contributions to reducing the ever-increasing weight of the vehicle.

2. Preliminary considerations regarding lightweight construction

Systems are known from the past which had a wall thickness of 2.0 mm. This reduction in wall thickness was achieved here by using a freeflowing PC/PBT blend. Following injection molding and before painting, the fascia was stiffened by backfoaming with polyurethane foam. Since the 2.0 mm wall thickness meant shorter flow paths, these panels were at that time injected directly onto the visible surface.

A very recent development of a Japanese automaker to enable series production of a bumper system with a wall thickness of 2.2 mm also shows the basic feasibility of reducing wall thickness from its usual figure today down to 2.8 + 0.3 mm.

The current PP types, optimized for paint adhesion, have, due to their relatively poor flowability over the course of production, gradually resulted in problems from flash in the mold parting surfaces.

The reason for this is the higher specific injection pressure required when using these poorer-flowing PP types. The pressure peaks arising in the combination with cascade injection molding give rise to considerable wear on the mold parting surfaces. The resulting flash cannot be reliably removed in its entirety. As a result injection molds in production need to be serviced very frequently, that is, scraped. Over time this leads to a significant reduction, depending on the geometry, in wall thicknesses in the direction of mold opening. Particularly with high quantities and the longer model cycles which are found, for example, with commercial vehicles, considerable wall thickness reductions have already been measured due to mold maintenance activities.

This was therefore another reason why the material had to be further developed in order to improve flowability while still complying with the material properties specified. These include in particular paint adhesion, ultimate tensile strength and low temperature impact strength.

More recent material developments go precisely in this direction. Since these modifications also have a higher modulus of elasticity, the idea arose of exploiting the much improved flowability and higher stiffness of these new PP types in the direction of lightweighting.

3. Implementation in prototypes

It was clear right from the start to all those involved that this idea should be implemented in a mold which had to be capable of series production as regards the gating concept, cooling and mechanical design. There was no question of converting a mass production mold at the end of mass production. In the first place that would have made another prototyping process necessary for after-sales production. Secondly, results would have been limited to a single automaker. For these reasons an existing mass-production mold was converted to 2.0 mm, thereby making available a first mass-production mold with a 2.0 mm wall thickness, one validated by having a standard hot runner, cooling system and split mechanism. What we learnt here was to subsequently provide us with design criteria and design guidelines during the series development of new vehicle panels.

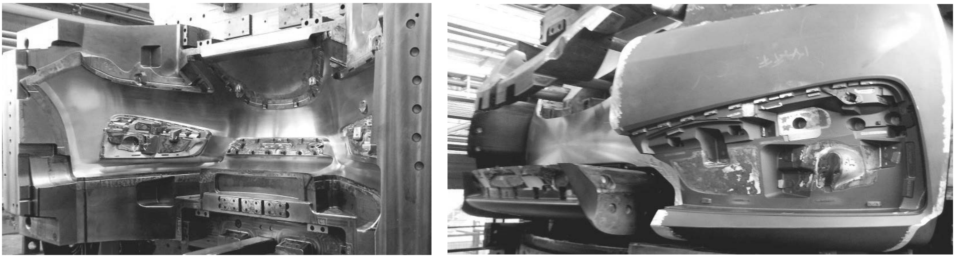


Fig. 1: Series mold 2.0 mm front bumper fascia

The mold was now extensively rebuilt to achieve a uniform wall thickness of 2.0 mm. The entire ejector side was reset and in the split area welded on over a large area. Simulation of rheological processes showed in addition that with the existing hot runner system there would be no problems filling the mold with the PP types modified for improved flowability, even in the case of 2.0 mm (Figure 1).

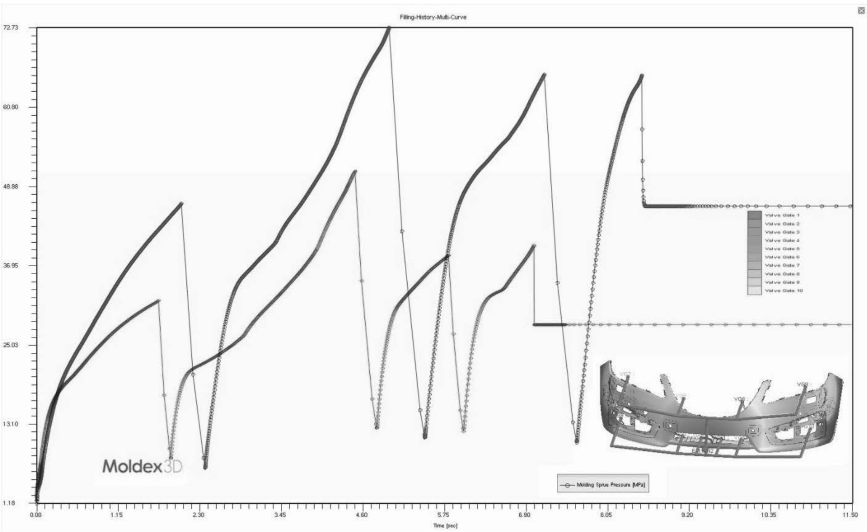


Fig. 2: MOLDEX pressure curve simulation wall thickness 2.0 mm (red) as compared with the original wall thickness of 2.8 mm (green)

In the selection of materials a wide range of candidates was examined. All material manufacturers of possible PP types were consulted regarding their suggestions. Several materials from a single manufacturer were even examined, since material releases may differ according to the OEM or material developments meeting the requirements of one OEM may not always be compatible with the requirements of other OEMs. Availability worldwide also played a rôle in material selection. Since different materials are used for bumpers in the US and the Asian automotive markets, in the material selection process even US and Asian materials and their manufacturers were taken into account in a test matrix.

Selection of 2.0 mm for the wall thickness arose from the following considerations. Firstly, this is the contribution for maximum weight saving and according to the results of rheological simulation just acceptable for series production. In addition, this wall thickness is critical as regards marks on the outer skin caused by splits, so that here, with the planned improvements in split fits, the results successively obtained are considerably more informative. With a 1:1 substitution of the mechanical values from the data sheet, wall thicknesses of 2.0 mm are also possible – but unfortunately these mechanical values cannot be obtained in the real injection-molded part by breaking down the molecular chains in the process. Currently a figure of 2.0 mm is therefore only theoretically possible and is conceivable here as an extreme example. Since, according to our cost-effectiveness calculations, the only economic way of equipping the fascia with distance sensors in the case of high production numbers would be by welding, the newly developed methods such as torsional ultrasonic welding (illustration) or welding with 45° ultrasonic sonotrodes (illustration) were selectively tested for the feasibility of a 2.0 mm wall thickness. And even the aspects of handling in production can be very much better assessed with a radical approach as compared with a reduction by a few tenths.

In addition, a wall thickness reduction of this kind was acceptable since, compared with the standard material, the new PP types have a significantly higher flexural modulus of elasticity (between 30% and 50%). Specimens were taken from sections of the component and in bending tests the flexural modulus measured in the direction of flow and transversely to it. From the sheet stiffness calculation to be used here, with, for example, a 50% higher flexural modulus and an unchanged stiffness, a possible wall thickness reduction to 2.45 mm was determined in comparison with the production part with 2.8 mm.

Results

Compared with the original material there is a measured weight advantage of 15%. The theoretical value of 28% with respect to the wall thickness reduction was not achieved since in the peripheral region and at the mounting positions the original wall thickness was left unchanged. In addition, high-MFI PP materials have a higher density value, resulting in a lower weight saving as compared with 'standard' types. The resulting components were now subjected to extensive testing.

Instrumented penetration test (table):

Thickness		2,8mm	2,0mm	2,0mm	2,0mm	2,0mm	2,0mm	2,0mm	2,0mm	2,0mm
Testing										
T1) VEM ISO 6603-A2 (T=23°C) a	-	1	1	1	1	1	1	1	1	1
Breaktype (1 - 9)	-	1	2	2	3	2	2	3	2	2
Energy @90% F-max	J	22,7	14,55	16,76	18,98	15,88	15,25	17,92	17,79	17,17
Energy S.D.	J	-	-	-	-	-	-	-	-	-
Force	N	1988	1389	1610	1962	1478	1464	1764	1698	1631
Force S.D.	N	-	-	-	-	-	-	-	-	-
Remarks:	-									
T2) VEM ISO 6603-A2 (T= -30 °C)	-	1	1	1	1	1	1	1	1	1
Breaktype (1 - 9)	-	4	See Pictures	9	9	9	4	9	9	8
Energy @90% F-max	J	37,87	-	22,03	8,72	21,33	25,29	23,88	24,17	26,54
Energy S.D.	J	-	-	-	-	-	-	-	-	-
Force	N	3533	-	2483	2418	2626	2593	2704	2737	2713
Force S.D.	N	-	-	-	-	-	-	-	-	-
Remarks:	-		No Result. Because sample isn't clamped it was pushed away by the impact of the dart.							

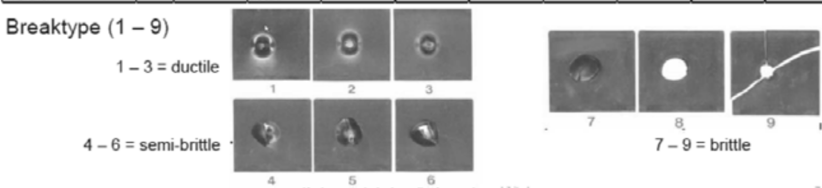


Fig. 3: Instrumented penetration test

At room temperature all specimens still reacted with ductile behavior. The reduction from 2.8 mm to 2.0 mm caused the original material to deteriorate only slightly from level 1 to level 2. In a direct comparison the maximum force decreased at room temperature by 30%. Other much stiffer types decreased by only 15% of the measured force. Other results were achieved in comparisons at -30 °C. As expected, all specimens with reduction to 2.0 mm exhibited a brittle fracture pattern. While the 2.8 mm sample in the original material still presented a relatively ductile fracture pattern, nearly all 2.0 mm specimens had brittle fractures. The level of maximum force had fallen by 25-30%. Only a single material from an American manufacturer reached the level of the original material. This is a material which was modified for the US market with regard to its low-temperature impact strength. However the measured flexural modulus of elasticity was still in the region of 10% higher than the level of the original material.

Results of the alternating climate test (within the tolerance according to TWT):

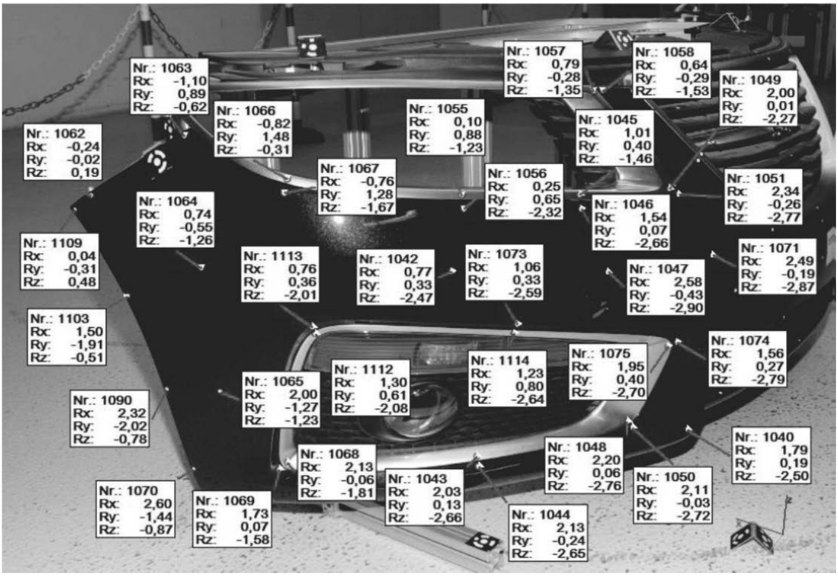
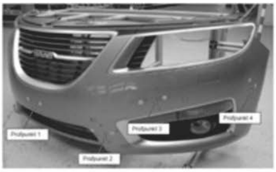


Fig. 4: Results of the alternating climate test (within the tolerance by TWT)

Tactile properties / buckling resistance by the indentation test:



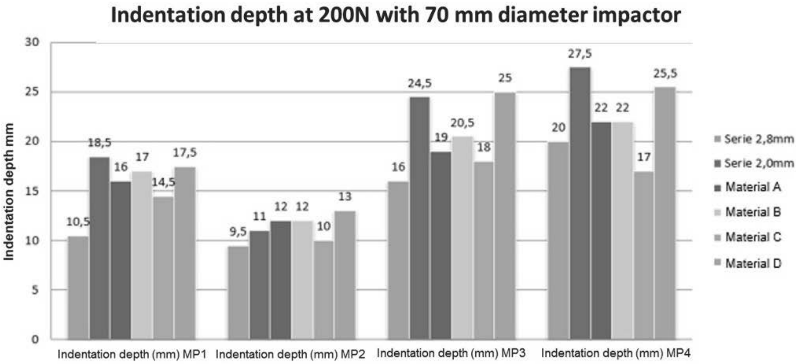


Fig. 5: Test results for tactile properties / indentation tests according to OEM 2 test requirements

Here deformations were measured at different selected measurement points in the simulated fitted state on the vehicle. These values are markedly dependent on the geometry but do show the real component behavior on the vehicle. Points 1, 3 and 4 are highly dependent on inherent stiffness in these areas, while point 2 is relatively close to a point of attachment. In some cases stiffnesses were achieved here on a level with those of the original wall thickness.

Results for paint adhesion

The results of testing paint adhesion on all materials included no failures in the cross-hatch test, the cross-hatch test following condensation with constant climate, and multi-stone impact tests following condensation with constant climate. There were however considerably more failures in our customers' steam-jet tests. Here there are significant differences on account of the test methods. Although the steam-jet test as specified by one German premium customer resulted in no failures, there was failure to fulfill the requirements of what are known to be the hardest specifications for steam-jet testing as issued by another German premium customer. However, with two of the materials tested the results show potentials which, following the appropriate modifications, lead one to expect an OK result.

Varnishing technology test project „Special thin wall technology" – SAAB 9-5 B

Hersteller	Material	OEM 1 Steamjet test		OEM 1 Steamjet test after climate		OEM 2 Steamjet test		OEM 3 Steamjet test		OEM 4 Steamjet test		OEM 1 multi rockfall test		OEM 2 multi rockfall test		OEM 1 multi rockfall test after climate	
		audited	n.i.O.	audited	n.i.O.	audited	n.i.O.	audited	n.i.O.	audited	n.i.O.	i.O.	n.i.O.	i.O.	n.i.O.	i.O.	n.i.O.
Manufacturer A		10	3	10	3	10	0	10	4	10	2	0 - 1	/	0,5	/	0,5	/
Manufacturer A		10	1	10	4	10	0	10	3	10	1	0 - 1	/	0,5	/	1	/
Manufacturer A		10	2	10	8	10	0	10	3	10	1	0 - 1	/	0,5	/	0,5	/
Manufacturer B		10	5	10	10	10	0	10	4	10	1	0 - 1	/	0,5	/	0,5	/
Manufacturer C		10	10	10	3	10	0	10	0	10	1	0 - 1	/	0,5	/	/	/
Manufacturer D		10	3	10	2	10	0	10	3	10	1	0 - 1	/	0,5	/	/	/
Manufacturer E		10	10	10	3	10	0	10	3	10	4	0 - 1	/	0,5	/	/	/
Manufacturer F		10	7	10	1	10	0	10	3	10	0	0 - 1	/	0,5	/		
Manufacturer G		10	4	10	5	10	0	10	4	10	0	0 - 1	/	0,5	/		
Manufacturer H		10	4	10	8	10	0	10	5	10	0	0 - 1	/	0,5	/		

Fig. 6: Paint adhesion results for various materials in various customer tests

Discussion of paint adhesion results

It was suspected that due to the more intense shear occurring when wall thickness is reduced to 2.0 mm, the molecules would experience a very high level of orientation and the rubber particles contained in the PP would thus be severely stretched. Overall this effect in our experience did not have any great influence in the relatively uncritical paint adhesion tests. However the higher degree of orientation could very probably have an impact in the case of the strictest test requirements in the field.

A microscopic examination shows the basic differences between the original wall thickness and the changed morphology of the rubber dispersion in the case of the reduced wall thickness. The very visible higher degree of orientation of the molecules gives rise to internal stresses in the material which, during the critical steam-jet test, relax due to the high mechanical compressive stress and can cause a cohesive failure in the material.

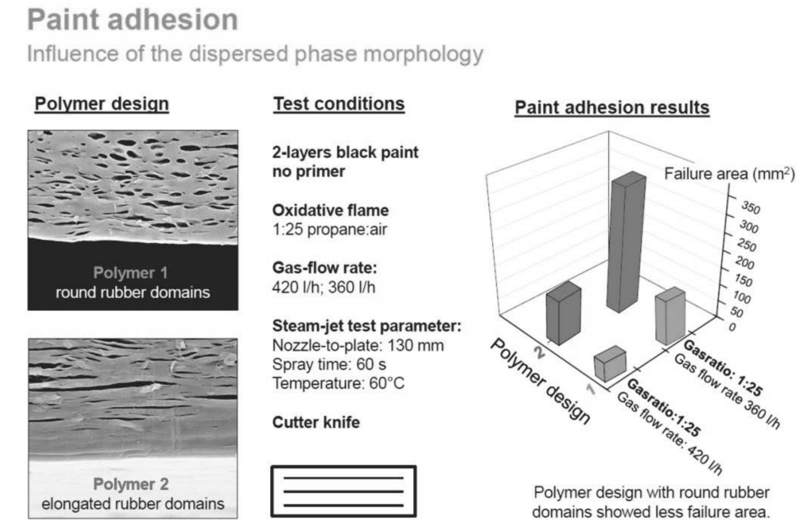


Fig. 7: Investigations of the Borealis company into the influence of morphology on paint adhesion

Although the steam-jet test is primarily concerned with the adhesion of paint to the substrate, the cohesion in the material itself does have an influence on the result of the paint adhesion due to the deep scoring used to simulate stone-impact stress. In the critical steam-jet test, the stress on the base material moves to a level which certainly has a negative impact on paint adhesion (see Figure 8).

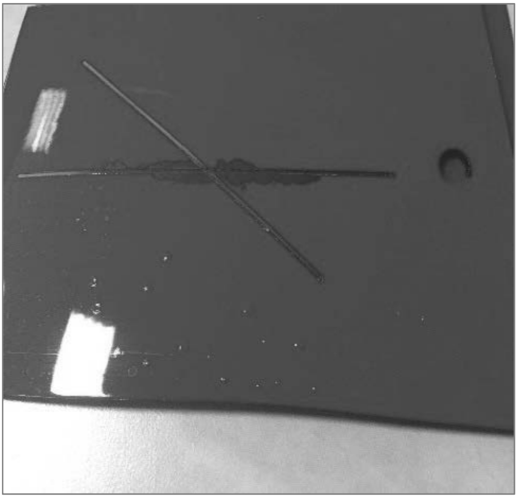


Fig. 8: Negative impact on paint adhesion due to cohesive fracture in the material (top); optimized material with improved paint adhesion (below)

Quality impression of the surface

In initial sampling for the 2.0 mm wall thickness, clear markings were seen in the case of critical colors in the areas of the side splits. They were however also already visible in a similar manner in the mass-production mold which had not yet been optimized to its final state. In order to achieve better results here, the mold, following initial sample inspection, was extensively investigated and revised. To obtain an accurate comparison of the effectiveness of these measures, only one side of the mold was modified and the results compared by quality assurance with the side left in its original state. The following optimization measures were implemented.

- Optimization of the spotting and pressure pattern of the nozzle and ejector sides
- Reduction of movements in the ejector side
- Minimization of the split offset.

After carrying out modifications, there was a marked improvement in the quality impression of the reduced 2.0 mm wall thickness. To the trained eye, slight marks could still be seen but at an acceptable level. The conclusion for Magna is that with thin-wall injection molding the mold design needs to be more complex. The minimal movements in the mold arising during compressive loading must be carefully simulated by the usual FEM methods. Special attention must be paid here to the mechanical stability of the split areas.

Joining methods

Bumper fascias are given a variety of additional components which serve to reinforce certain areas or, depending on the vehicle configuration, to accommodate radar units, parking distance sensors and antennas. These components are connected directly to the Class A surface. The usual method is either to glue the housings to the bumper fascia with double-sided adhesive tape or to use ultrasonic needle-package welding. According to our cost-effectiveness calculations, gluing is not the best solution with larger production quantities. Ultrasonic welding of the brackets to the bumper fascia by needle-package sonotrodes is only possible without leaving marks when the wall thickness is selectively increased from 2.8 mm to 3.2 mm.

The aim was to find a welding process and optimize it to the point where specifications regarding compressive strength and absence of markings could be satisfied, as well as additional expenses being avoided in production.

Torsional ultrasonic welding and 45° ultrasonic sonotrode welding were here developed to series production readiness in collaboration with the respective development partners. Special sonotrodes are used for both methods: they make it possible not only to weld to lower wall thicknesses in Class A quality but also to yield even higher pull-off values / better welding results than with conventional US sonotrode welding.

The 'thin wall capability' of the two methods was first tested on panels of different wall thicknesses and then validated in prototypes with 3D specimens.

Operating principle of 45° welding: with 45° welding the sonotrodes are arranged with the angular orientation mentioned and this thus creates not only a welding angle of 90° to the surface but also a frictional effect which runs at 45°.

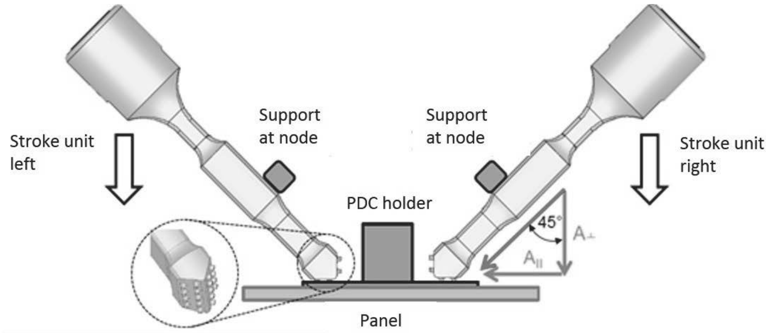


Fig. 9: 45° sonotrode welding (courtesy of the PPtech company)

With 45° welding, so-called 'crescent sonotrodes' are used to obtain an optimized welding pattern for holder and bumper. These enable a shortened leverage between the holder and the welding point, and thus also a greater pull-off force.

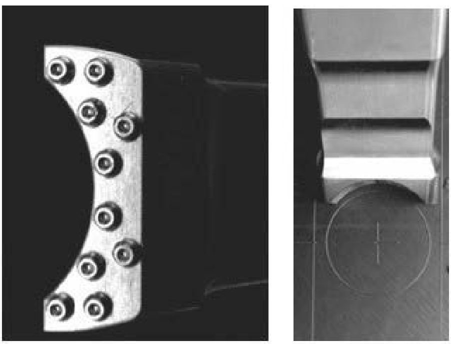


Fig. 10: 45° welding, crescent sonotrode (courtesy of the PPtech company)

With torsional US welding, round sonotrodes are used which allow all-round welding and can thus drive pull-off values to extreme heights. However, this is not absolutely necessary and can even be optimized in the course of class A quality requirements.

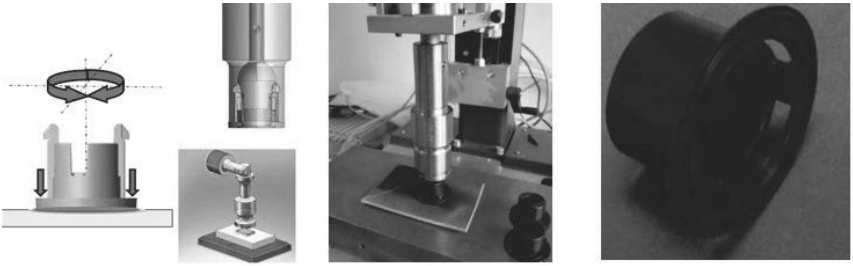


Fig. 11: Welding with torsional US sonotrode

The torsional movement of the sonotrode is due to ultrasonic excitation in the micron range and achieves a very satisfactory all-round welding even after a very short welding time. Optimization in series production to a Class A welding result is finally effected in the harmonization of the weld rib and the weld geometry as well as with the bumper package for installation of the sensors.

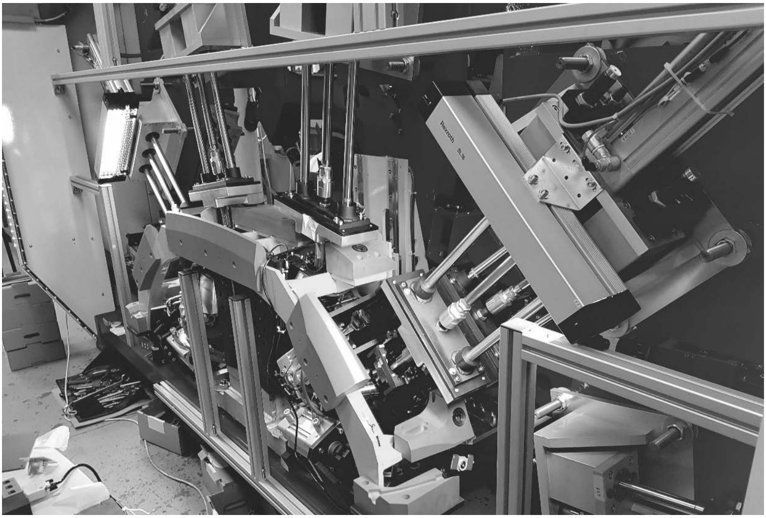


Fig. 12: Skoda production system with torsional ultrasonic welding

Summary and outlook

Following successful series implementation of thin-wall technology in what is now four bumper projects, Magna Exteriors is convinced that the thin-wall technology will make its entrance even into the absolute premium segment of the automakers and even today can already fulfill their requirements. Thin-wall technology will however not stop at a value of 2.5 mm but will at a very early stage master the next evolutionary step due to the development of new materials. Magna Exteriors is preparing itself for this in the form of rigorous 'best in class' processes in injection molding, painting and assembly and will respond with innovative solutions to this on-going trend.

Just as we are developing new markets such as aerodynamic products, composite manufacturing and large exterior modules (side doors, for example), so too will Magna Exteriors continuously further optimize its existing products in order to be a world-class producer of exterior plastic components in all fields.

<u>References:</u>

[1] Basell documents

[2] Borealis documents

[3] PP Tech documents

[4] Telsonic documents

[5] Longitudinales und torsionales Ultraschallschweißen – ein Verfahrensvergleich / *Longitudinal and torsional ultrasonic welding - A comparison of the processes* Prof. Dr.-Ing. Michael Gehde, Dipl.-Ing. Sven Friedrich, Dipl.-Ing. Rene Fuhrich, TU Chemnitz, Chemnitz

Development of a filler-cap hinge made of recycling material

M. Thurmeier, M.Eng., **C. Horbas**, Dipl.-Ing. (FH) **F. Wagner**,
AUDI AG, Ingolstadt

Abstract

This contribution concerns the development of the new generation of filler caps which are continually becoming larger due to the connections being added. This means more and more requirements applicable to the material. This is described below in the example of the filler-cap hinge.

1. Motivation

Recent years have seen an enormous increase in complexity due to the technical development of vehicles. In addition to the fuel filler opening, other connections for SCR technology and electromobility are found more and more frequently. The size of the filler cap or the filler cap module is also directly related to this. A new, reinforced material is required which will be able to compensate for the higher forces arising from the larger surface.

2. Component design

Component design must be preceded by a consideration of the various requirements. Not only mechanical requirements must be investigated but also without fail quality, thermal and material requirements and also aspects relating to production. The different load cases and influencing factors have resulted in the main requirement made of the component being rigidity.

3. Material production, material, component production

In the manufacture of body components, woven and nonwoven fabrics are made from carbon fiber and then cut to the sizes required. This operation results in fiber remnants as a by-product. These are in turn used for making a PP CF30 injection-molding compound with very good specific properties.

The material not only has a low weight but also high stiffness and a low thermal expansion. In comparison with the PA6 GF50 series-production material, use of this PP CF30 material meant a weight saving of around 38%. Furthermore, PP does not absorb water and thus better satisfies the high quality criteria than a PA.

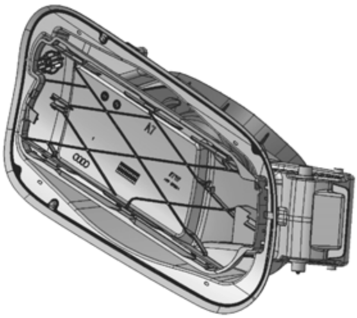


Fig. 1: Complete view of the filler cap module

Lightweight material with class

Rear apron made of extremely low density polyurethane

Dipl.-Ing. (FH) **C. Bauernfeind**, Dr. Ing. h. c. F. Porsche AG, Weissach;
Dipl.-Ing. **E. Blees**, Polytec Group (Polytec Car Styling), Hörsching, Österreich

Abstract

The GT3 RS is currently the most extreme model in the Porsche 911 family. As a link between the street-legal sports car and the pure racing cars, this model has to meet the highest demands for lightweight design and performance no matter what. To achieve this it is essential to exploit to the full the technical possibilities of every individual component.

In the rear bodywork of the GT3 RS, a lightweight version of filler-reinforced polyurethane (PUR-RRIM) comes to series production for the first time due to the close and partnerlike collaboration of the development partners involved. This new materials technology can successfully demonstrate its full potential in this component and reduce component weight by 23% while maintaining all necessary mechanical and qualitative properties.

1. Introduction

The main focus in the body design of the Porsche GT is on linking function with maximum lightweighting without thereby negatively impairing quality and robustness in comparison with series Porsche vehicles. On the contrary – a higher level of excitation due to an almost racing car chassis plus intensified on-the-limit thermal and aerodynamic operating conditions demand a maximum load-bearing capacity of the components.

In order to achieve a huge increase in downforce and at the same time to once again improve performance on the racetrack as compared with its predecessor, in the current 911 GT3 RS not only were many areas modified in chassis, powertrain and electrical systems development but also almost every body component. Alongside fenders and hood made of carbon fiber, a roof made of the finest magnesium sheet and a carbon-fiber trunk lid with a lightweight spoiler structure, the lightweight rear apron made of polyurethane makes an important contribution to the overall weight balance sheet of this rear-engined sports car.

If the front and rear aprons of GT cars in the past were made of standard polyurethane (PUR-RRIM) with fiber reinforcement, a lightweight PUR-RRIM is now used in the rear of the current GT3 RS, thus achieving a weight saving of over a kilogram at the rear axle. In addition to the correct choice of material, an optimum component design and a sophisticated manufacturing process contribute to this remarkable result.

Fig. 1: Porsche 911 GT3 RS

2. Material

The innovative PUR elastomer system used in this project for the first time worldwide in a series application is characterized by an extremely low density. Weighing less than one gram per cc this material is even lighter than water. In comparison, the density of steel and aluminum sheet lies around 8 and 3 grams per cc respectively. The lightweight material Bayflex® Lightweight is a development of Covestro Germany AG, Leverkusen (formerly Bayer MaterialScience) which was created in close collaboration with 3M Germany GmbH, Neuss, and the processors Polytec Car Styling, Hörsching, Austria. Thanks to this material, the rear bodywork weighs about 1.2 kilograms less than its counterpart in the predecessor model. This corresponds to a weight saving of around 23% and is thus lighter than comparable bodywork parts made of polypropylene.

The considerably higher density of the Bayflex® 180 used previously (also a tough and resilient PUR elastomer system from Covestro) is basically due to the fact that the mineral fibers incorporated to increase strength and rigidity (density 2.85 g/cm³) make up 17% of the total weight. The material manufacturer was therefore looking for alternative fillers and reinforcing materials in order to reduce density and to achieve an even lighter PUR elastomer.

The solution finally arrived at was to use 3M glass bubbles (hollow glass spheres) in combination with lightweight, milled carbon fibers instead of the mineral fibers. These microscopically small hollow spheres with an average diameter of 20 μm serve as a functional lightweight filler. They are made of borosilicate glass and combine a very low density of less than 0.6 g/cm³ with a high compressive strength (important for processing) of up to 1100 bar. The hollow glass spheres are chemically inert, insoluble in water and finely dispersed in the PUR reaction system.

The milled carbon fibers have the job of providing the PUR system with a good level of strength and rigidity. Their low average length of only 150 μm and the shape of the hollow glass spheres means that the PUR material, unlike the mineral-fiber-reinforced Bayflex® 180, gives the component virtually isotropic properties, thereby facilitating the engineering and simulative design of the components for different loading cases. The shortness of the carbon fibers means that they can be sourced from the remnants of fiber mats coming from the production of carbon-fiber-reinforced plastic components. These recyclates give the PUR materials uniform mechanical properties and are at the same time significantly more cost-effective. Furthermore, this waste recovery closes material cycles and is therefore particularly sustainable.

The total weight of the fillers is 13%, of which the hollow glass spheres make up 10% and the carbon fibers 3%. Due to the low density of the lightweight filler this corresponds to a very high volume percentage for the fillers of almost 25%. In comparison, conventional RRIM components with 17 vol% mineral fibers contain only about 7 vol% filler. During processing, the material in contact with the mold forms a thin skin. The surface thus contains no fillers and can therefore be painted to the highest quality standards.

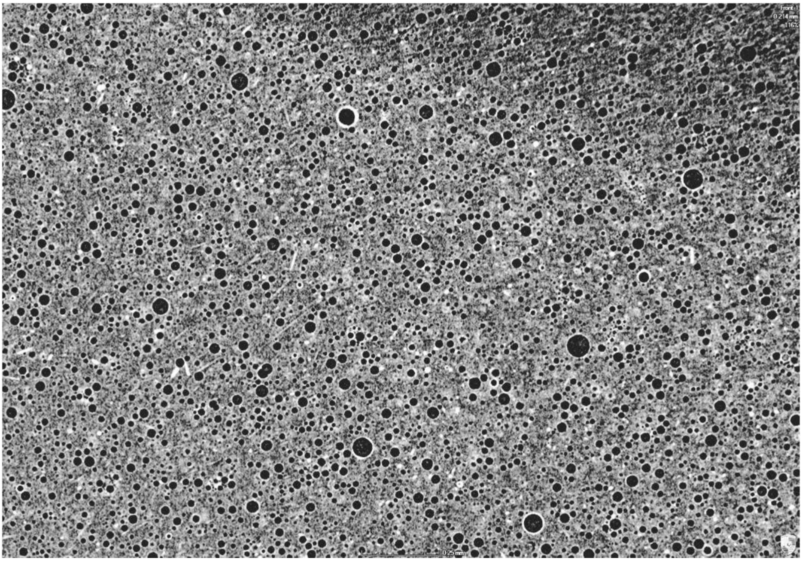
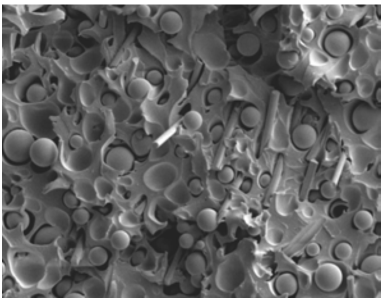


Fig. 2: Microsection (Porsche)



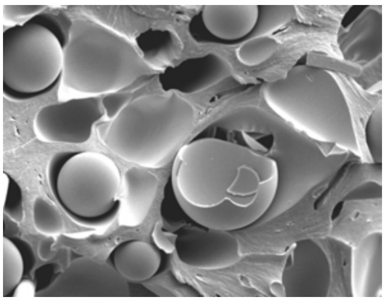


Fig. 3, 4: REM (Polytec)

The high filler content of the new material resulted in not only lower tensile strength and elongation at break but also a drastic reduction in impact strength in the case of painted components. This had to be compensated by design measures in the component development of the GT3 RS rear apron. Intensive further development of the material by Polytec resulted in an RRIM lightweight material of the second generation with mechanical properties which were in all cases comparable to those of conventional RRIM parts, and sometimes even better. In particular, cold impact strength could be quadrupled as compared with the original material.

Table: Comparison of the mechanical properties of conventional and lightweight RRIM parts of the second generation (values for annealed components)

		RRIM 17% MF	**RRIM Lightweight**
Density	g/L	1.1 … 1.2	0.9 … 1
Hardness (Shore D)	-	55 … 65	
Flexural modulus longitudinal/transverse	MPa	>1000 / >650	>1000 / >800
Tensile strength	MPa	20 … 30	15 … 20
Elongation at break	%	150 … 200	100 … 150
Impact strength[1] RT/-25 °C	kJ/m²	no break / > 15	no break / > 25
Heat deflection tem-perature HDT	°C	135 ... 145	

[1] Charpy impact strength

3. Component development

The product specifications form the basis for component development. All technical, styling-related, qualitative and legal requirements applicable to the bodywork are defined in these specifications. For example, a rear apron must pass the pendulum impact test, which simulates a parking knock at defined impact heights and angles. Installed lights must remain fully functional here, no sharp edges may result and no paint or base material go missing. In this test the lower elongation at break and impact strength of lightweight polyurethane of the first generation initially led to a material fracture in the area of the reflector mounts. It was only when the edges in question were rounded off locally on the inside of the component that material failure was entirely prevented.

In addition, the aim was to realize the component wall thicknesses of a comparable part made of polypropylene. With a basic wall thickness of 2.8 mm this target was even exceeded. In some edge areas, wall thicknesses measured 3 mm in order to improve local rigidity and also to optimize the flow of materials during the manufacturing process. In other areas, the wall thickness could be thinned down even more. The rear apron of the GT3 RS currently in series production thus weighs the same as a polypropylene bodywork component of the 911 Carrera.

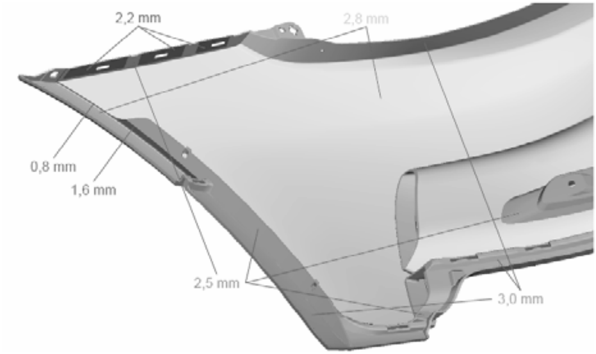


Fig. 5: Wall thickness distribution

Further complete-vehicle tests, such as high load endurance, crash testing, corrosion testing and wind tunnel tests, must be completed without objections being raised.

Before the rear apron receives unqualified development release for series production, it also undergoes a number of component tests. Sections are removed and tested for everyday suitability using specified test media.

The painted plastic surface must be resistant to gasolines, oils and the most diverse cleaning agents. Under UV irradiation it must not age faster than the surfaces of adjacent components and must meet the emissions requirements of all countries in which the vehicle will subsequently be sold. Plastic clip connections are tested in all trials and must not fail. Should rattling noises occur in 'squeak & rattle' testing on the hydropulse test stand or in endurance testing – as a result of material fatigue, for example – the design of the plastic components must be modified accordingly.

Despite all of the lightweighting measures, the rear bodywork must still satisfy the strictest requirements with regard to visual appearance and surface quality analogous to comparable components of a high-volume production vehicle. The alternating climate test exposes the component to fluctuating temperatures and air humidity and, up to the specified limit values, must not result in any damage whatsoever to the surface. In the first test runs a visible wave formation appeared in the area between the tail lights and was caused by excessive tension in the component. A specific adjustment of its attachment to the vehicle structure allowed the rear bodywork component to locally expand longitudinally under the influence of temperature, which prevented component tensions and thus wave formation on the surface.

One major challenge in the development of the rear bodywork of a rear-engined sports car is to shield plastic components from the very high exhaust gas temperatures. Close proximity to the hot mufflers and exhaust pipes requires the use of special heat shields and also shielding panels of thermally stable plastics in order to protect the polyurethane from being damaged.

4. Process development

In the reaction injection-molding process the two components, polyol and isocyanate, are mixed under high pressure in a mixing head and injected into a mold where they react to the polyurethane. In most cases, glass or mineral fibers are added in a proportion of 10-20% to improve mechanical properties.

The fillers or reinforcing materials as a rule are mixed into the polyol. Mixing-in the light-weight filler is a special challenge. Due to their markedly low density the hollow glass spheres tend to float in the relatively viscous polyol. If good and reproducible results are to be achieved quickly with the mixing, all major parameters such as tank diameter and fill level, the geometry of the agitator and also the stirring speed and force must be mutually adjusted. In addition, the viscosity of the polyol component increases during the mixing process. This effect is particularly pronounced with the RRIM Lightweight on account of the very high filler content in the polyol (about 45 vol%). To keep the material flowable, a minimum temperature must be maintained over the entire supply section from the tank to the mixing head. For this reason, not only are the tanks and mixing heads under the usual temperature control but also all lines carrying polyol.

In the same way, great care is given to powerful temperature control of the mold in order to ensure a uniform filling of the mold from the gate to the farthest points of the cavity.

After demolding, the rear bodywork components are placed on support structures to prevent warping. This is normal procedure with large RRIM components and absolutely necessary with lightweight components on account of their thinner walls. Equally it is important to ensure good support for the mold contour when positioning on painting frames as otherwise sink marks, other marks or warpage may occur. In the subsequent processes (trimming, cleaning and pretreatment, painting) the lightweight components are processed in exactly the same way as conventional RRIM parts.

5. Conclusion and outlook

With the successful industrialization of the GT3 RS rear apron, the lightweight polyurethane elastomer now forms the basic material for body parts of future Porsche GT cars. In the near future, the material will no longer be used just in the rear but also in the front bodywork of a GT3.

Currently the development partners are focusing on expanding the performance limits of the material and the associated RRIM technology. The aim is, for example, to raise the level of mechanical properties in order to further reduce wall thicknesses and thus component weight. One important emphasis is on reducing production costs to the extent that even in greater quantities they will at least be on a level which is typical of injection-molded polypropylene.

Development work is also proceeding in the field of fillers. 3M is currently expanding the range of hollow glass spheres for use in different applications. In the meantime the range covers mean nominal densities from 0.125 to 0.60 g/cm³.To expand its range of applications, product variants with modified properties are being continually added. One example is hollow glass spheres which, in comparison with the PUR material presented here, result in more impact-resistant materials with only a slightly lower flexural modulus and a minimally higher density. These foams lend themselves to use for highly impact-stressed components. Even beyond PUR systems, the hollow glass microspheres are suitable for various types of polymers. The manufacturers are according working in parallel on the development of high-pressure resistant variants for the injection molding of lightweight thermoplastic components.

Active aerodynamic advancements in vehicle underbodies

A. Povinelli, **M. Matthews**, Magna Exteriors, Troy, Michigan, USA;
Dr. **J. J. Laux**, Magna Management, Cham, Switzerland;
J. Goetzelmann, Magna Exteriors, Sailauf

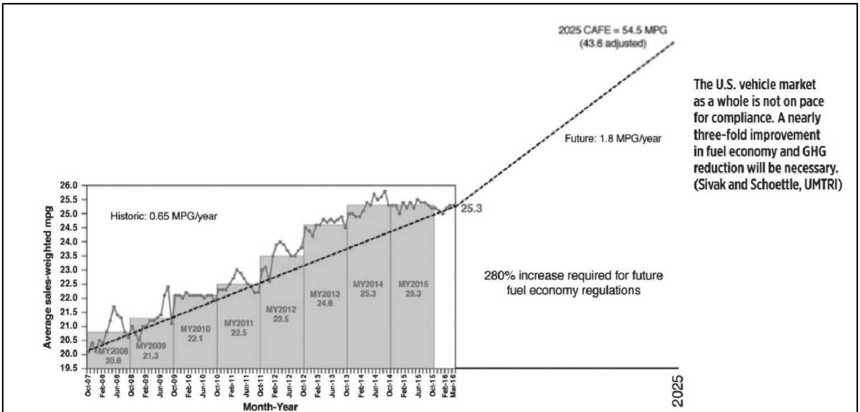
Abstract

Global fuel economy and carbon emissions regulations are increasing year over year and OEMs, on average, are below requirement targets. To help manufacturers meet their goals, Magna Exteriors, a division of Magna International, has accelerated development work in active aerodynamic systems, supplementing powertrain and styling improvements, to bridge the gap.

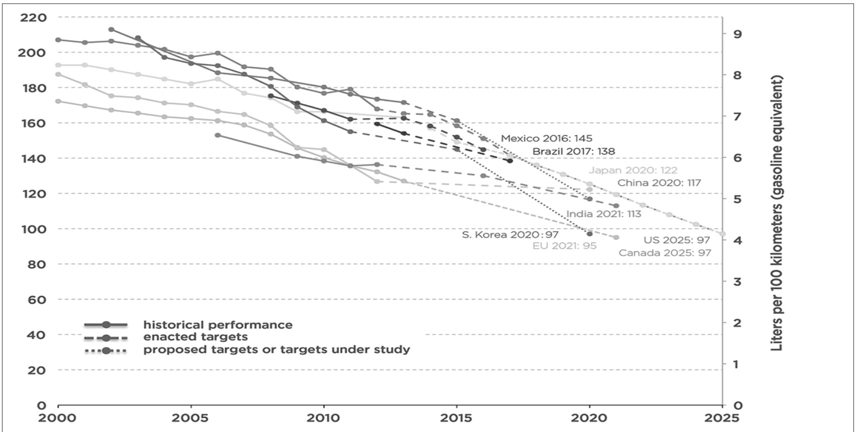
A vehicle's aerodynamic profile is a major contributor to its energy consumption, be it fossil fuel or electric vehicle (EV) battery power, and Magna's innovative solutions combine styling with aero to take drag-reduction technology to a new, higher level. Active aerodynamic solutions from Magna include exterior vehicle systems such as active grille shutters (AGS), active front deflectors, active underbodies and others.

1. Introduction

In the USA, as CAFE standards increase, manufacturers are not advancing fast enough to meet the 2025 requirement of 54.5 mpg.



Source: Automotive Engineering Magazine, SAE, September 2016



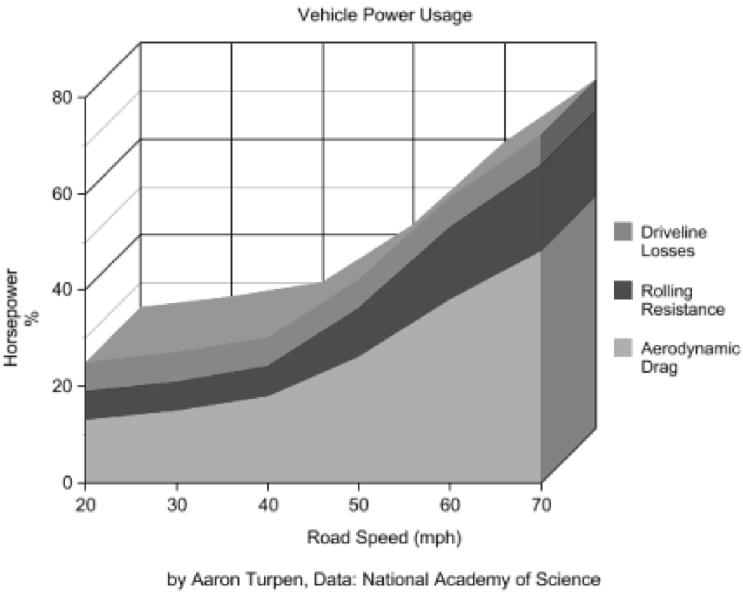
Source: The International Council on Clean Transportation

Magna Exteriors anticipated the need for aero technologies to help automakers meet global targets. We have been in the active aero market for nearly a decade and currently have over 14 AGS in production, including one visible, class-A type. Magna works with multiple OEMs and ships more than two million units globally each year. Magna is also creating new active aero applications that will be implemented around the entire vehicle in an effort to find every opportunity to reduce drag. This experience, and our drive to innovate, has positioned the company to develop the solutions needed by OEMs to meet future regulations.

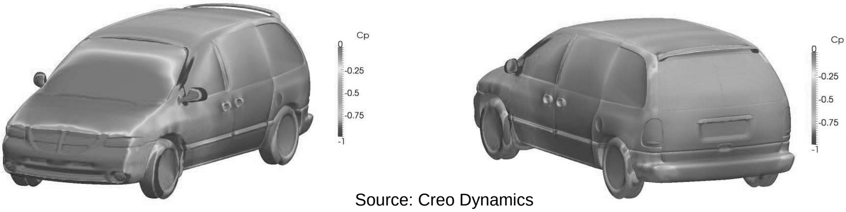
2. Aerodynamic drag impacts

The Environmental Protection Agency (EPA) and the New European Driving Cycle (NEDC) both have substantial requirements for speeds over 40 mph (64 kph): 34% and 19% respectively. The proposed Worldwide-harmonized Light duty driving Test Procedure (WLTP) standard is even higher than NEDC at 33%. Components of vehicle drag include ram air, skin friction and wake, and are roughly 55%, 10% and 35% respectively.

Since about 50% of the energy used at 40 mph (64 kph) is to overcome aerodynamic drag, solutions that reduce drag have the largest opportunity to make significant impacts toward meeting requirements. Additionally, due to the velocity squared impact on drag, the benefits of these systems increase quickly as speed increases.



Vehicle aerodynamic drag is comprised of three main components: ram air pressure on the front of the car, skin friction, and the wake behind the vehicle. Although skin friction is a small percentage (about 10%) of the full aero drag, underbody turbulence and airflow separation can drastically affect the wake component of drag.



Source: Creo Dynamics

Figure: Mapping of the coefficient of pressure on a vehicle showing ram air pressure, skin friction and wake.

3. Vehicle styling impacts

Vehicle aerodynamics, through styling, have improved greatly over the years. Coupled with continuous powertrain improvements, fuel consumption and emissions have continually decreased.

1975

1995

2016

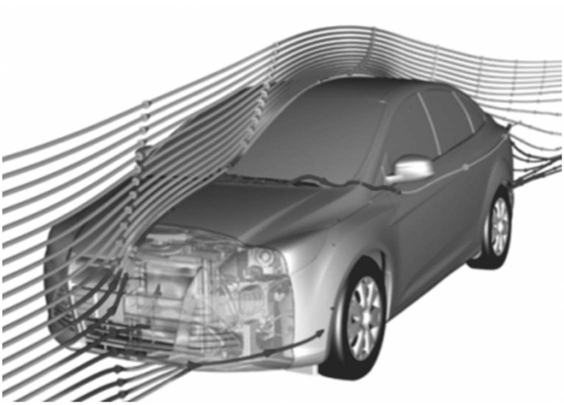
But regulations on lighting, visibility, pedestrian protection and low speed impact, as well as visual appeal, have limited optimal drag profiles.

The industry to date has come a long way towards reducing drag. Improved virtual analysis and correlation through physical testing will allow for further reductions. However, significant future improvements require active aerodynamic solutions.

4. Growth of active aerodynamic technology

AGS were the first widely used application of active aero technology and can now be found on many cars and trucks in production worldwide. An AGS can be visible, integrated with vehicle grilles or behind grilles, like traditional non-visible AGS. There are many variables, such as vehicle type, vehicle styling and engine efficiencies that influence the benefits of active aero grilles, hence the benefit of drag reduction varies.

Airflow through the vehicle front-end (grille, fascia opening) and into the engine compartment is very restrictive. A closed AGS modifies the ram air by diverting air around the vehicle, which is a less restrictive path, thus reducing drag. It also has the added benefit of ‘sealing’ off the engine compartment in cold weather. This helps achieve faster engine warm-up to meet and maintain optimal operating temperature, which further reduces emissions and fuel consumption.



There are other active systems on the market today, typically aimed at reducing lift or for niche vehicles. Our goal is to provide cost effective drag reduction solutions to the entire market.

5. Development considerations and methodology

Magna has extensively researched and investigated many kinds of active aero systems including, but not limited to, front deflectors, wheel spats, underbody panel(s), diffusers and rocker panels. Our experience in developing and manufacturing drag reduction components has shown great promise for active aero underbody systems. We identify potential benefits for these systems by:

- Understanding vehicle drag characteristics
- Identifying areas for improvement
- Designing, meshing and running computational fluid dynamics (CFD) analysis to determine potential benefits
- Using physical wind tunnel testing for drag reduction validation and influencing factors
- Correlating CFD to physical testing
- Creating the system framework through design and engineering
- Identifying opportunities for integration and optimization.

These processes enable Magna to offer unique and innovative solutions to customers with great confidence.

6. Innovations in active aerodynamics

As the first broadly used solution for drag reduction, AGS have seen considerable growth globally and are considered fairly common in today's market. Although Magna ships millions of AGS yearly, we work diligently toward continuous improvement to ensure a better product for a better price. Magna has multiple patents around AGS and has one of its patents in production.

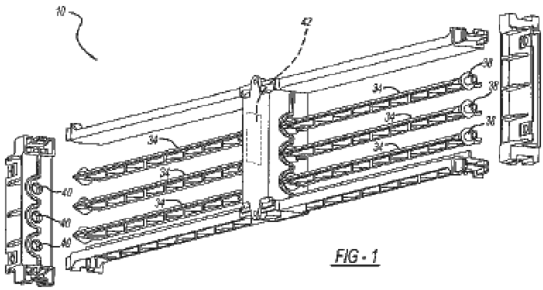
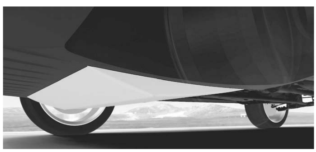


FIG - 1

In the near future, Magna will supply the automotive industry with multiple aero technologies, with a strong focus on modifying underbody airflow through innovative active front deflectors, active underbody panels and active rear diffusers.



As we move forward with new technologies, we never lose focus on what might be next in aerodynamics. Virtual systems and real-time airflow mapping and control are just a couple of things we are investigating.

As expected with an 'active' aerodynamic system, actuation is paramount to ensure an effective system. In coordination with Magna's closures and mirrors groups, Magna Exteriors has developed a LIN-based, sealed, high-speed, high-torque actuator with an internal clutch to meet the demands of our new aero systems. This makes Magna one of the only fully vertically aligned active aerodynamics suppliers in the automotive market, allowing OEMs to source a complete solution.

7. Considerations for application

As the demand for improved aerodynamics increases, it is necessary for automakers to consider the application of active systems from the start. By analyzing the vehicle with active aero early on (during clay design stage), the studio can understand the impact of aero on styling. Additionally, multiple aero systems can be analyzed together to ensure they work in harmony, which will provide the greatest benefit.

Once optimal system design, shape and location are known, proper packaging can be protected. This allows for optimized travel, which is a key driver in system function, durability and reliability.

8. Conclusion

It is clear that active aero technologies must be applied to meet future fuel and emissions requirements as powertrain improvements and vehicle styling cannot bridge the gap. By incorporating active aero early in the design process, automakers and consumers get the biggest possible benefits of drag reduction. Magna continues to lead in this area by providing innovative, cost-effective and high-quality solutions.

Improved crash simulation of endless-fiber-reinforced thermoplastics – organic sheets

Dipl.-Ing. **M. Franzen**,
Ford Werke GmbH, Research & Innovation Center Aachen, Aachen;
Dipl.-Ing. **G. Oberhofer**,
MATFEM Partnerschaft Dr. Gese & Oberhofer, Munich;
Dipl.-Ing. **R. Schwarzer**,
Kirchhoff Automotive Deutschland GmbH, Attendorn

Abstract

Endless-fiber-reinforced thermoplastics show a high potential for weight reduction in the automotive area. However these materials feature a very complex mechanical behavior due to the use of relatively soft and ductile thermoplastic matrix material in combination with stiff and brittle endless fibers.

Within the current crash simulation codes no suitable material models are available to simulate these complex materials correctly and adequately, such as, for example, correctly predicting the elastic, plastic and fracture behavior in dynamic impact loadings. MATFEM Partnerschaft Dr. Gese & Oberhofer in collaboration with the Ford Research & Innovation Center Aachen and Kirchhoff Automotive Deutschland GmbH have developed a material model for crash simulations in order to be able to correctly predict deformation and failure behavior of this complex material group. The MF-GenYld+CrachFEM material model is used within RADIOSS® and LS-Dyna®.

Automotive prototype parts have been manufactured and subjected to various load cases to validate the advanced material model by correlating the CAE models with the test data in terms of measured force-deflection curves and observed material failure. The advanced material model leads to a very good correlation in terms of deflection, deformation and fracture behavior.

1. Motivation

Today the automotive industry is challenged by a continuously rising number of demands exerting a strong influence on the development process. The need for CO_2 reduction and hence the resulting need to reduce the vehicle weight as well as the need to constantly improve occupant and pedestrian protection makes it necessary to fully utilize the deployed materials as efficiently as possible. In addition, product development has to be economical with respect to development time and costs. For every single component it must be decided which material is suitable for satisfying the full number of defined requirements in an optimized way. [1]

In order to be able to meet the increased requirements within a framework of shorter cycle times and rising cost pressure, car manufacturers are intensifying the use of computer-aided engineering tools for the various stages of the development process. For the crash simulations the explicit Finite Element Method (FEM) has been applied for a long time. However this process can only be successful when the numerical methods are capable and there is a high confidence level. [1]

Especially for the simulation of continuous-fiber-reinforced thermoplastic materials (organic sheets, for example) there is a great demand for improved crash simulation methods. These materials show a high potential for cost-effective weight reduction in the automotive area. However these materials feature a complex mechanical behavior. Depending on loading in relation to fiber orientation, this behavior can be very stiff with brittleness and no plasticity or soft with ductile behavior and significant plasticity.

Commercially available FEM programs have limitations regarding continuous-fiber-reinforced thermoplastic crash-prediction capability. The matrix material is generally only represented in a simplified manner. Visco-elasticity, visco-plasticity and fracture is not adequately described. For this reason the Ford Research & Innovation Center Aachen, Kirchhoff Automotive Deutschland GmbH and MATFEM Partnerschaft Dr. Gese & Oberhofer started a project to characterize organic sheets in detail and extend the material model MF-GenYld+CrachFEM for crash simulations. The material model has been globally implemented at the Ford Motor Company since 2008.

2. Technical approach

To correctly predict the mechanical behavior of continuous-fiber-reinforced thermoplastic parts the Ford Research & Innovation Center Aachen in cooperation with the companies MATFEM Partnerschaft Dr. Gese & Oberhofer and Kirchhoff Automotive Deutschland GmbH have developed a methodology for significantly enhancing crash simulation quality which can be used in the development process at the Ford Motor Company. The MF-GenYld+CrachFEM material model is used within RADIOSS® and LS-Dyna®.

One basic requirement for this approach is advanced physical material testing in order to identify the complex material behavior in all the required areas. Once these tests have been performed the material cards are set up to supply the MF-GenYld+CrachFEM material model developed by MATFEM. Within the Ford Motor Company this material model is coupled to RADIOSS® and LS-Dyna® and is installed on a global high-performance workstation cluster.

MF-GenYld is a modular plasticity model and CrachFEM is a module for a comprehensive failure prediction. The MF-GenYld+CrachFEM material model can be linked to different explicit finite element codes (such as ABAQUS/Explicit®, LS-Dyna®, PAM-Crash® RADIOSS®). MF-GenYld offers various yield loci, all of which may be combined with different hardening models in order to reflect the observed behavior of a wide range of metallic and polymeric materials. The MF-GenYld+CrachFEM material model is able to represent specific effects of non-reinforced, short-fiber-reinforced and continuous-fiber-reinforced polymers which are relevant to crash applications:

- Visco-elastic behavior (simplified approach) in combination with orthotropic elastic behavior
- Visco-plastic hardening behavior with different orthotropy for tension and compression
- Anisotropic hardening behavior (different hardening for tension, compression and shear)
- Plastic compressibility
- Significant plastic strains before fracture
- Strain-rate- and stress-state-dependent fracture valid for shell and solid discretization
- Anisotropic fracture behavior (stress- and strain-based)

This approach means that different types of polymer can be treated with one single approach as shown schematically in Figure 1.

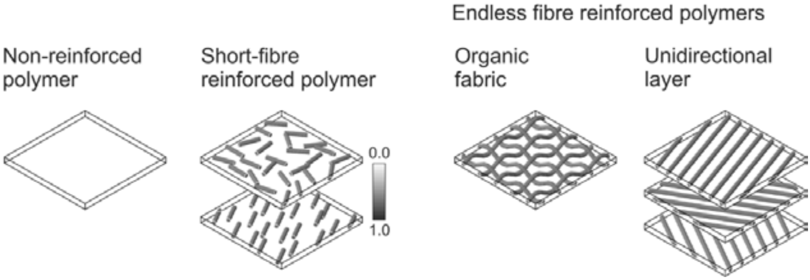


Fig. 1: Different types of non-reinforced and fiber-reinforced polymers

Within this study a characterization method similar to the implemented standard approach for short-fiber-reinforced thermoplastics (SFRT) has been used for organic sheets. Compared to SFRT the degree of anisotropy (elastic, plastic and failure) can be more pronounced. In fiber orientation a comparatively small amount of plastic deformation before fracture can be observed. In off-axis orientations a highly ductile behavior with little hardening can be observed as shown in Figure 2. This characteristic behavior can be stress-state-dependent (for example, different for tension and compression).

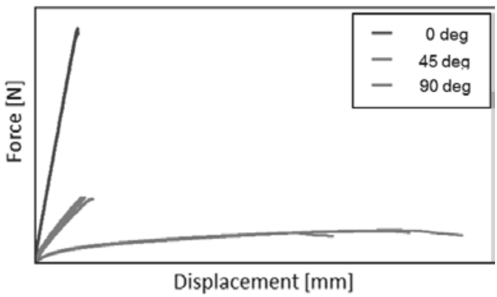


Fig. 2: Typical hardening behavior in uniaxial tension of the investigated organic sheet

The investigated material is described on the assumption of orthotropic behavior. This assumption is reasonable as the thin-walled structure has two perpendicular planes of symmetry. The simplification here is that orthotropy remains constant over deformation. This simplification can be avoided in the future by moving to generally anisotropic approaches in MF-GenYld+CrachFEM. Modules which are used for the material characterization are highlighted in Figure 3.

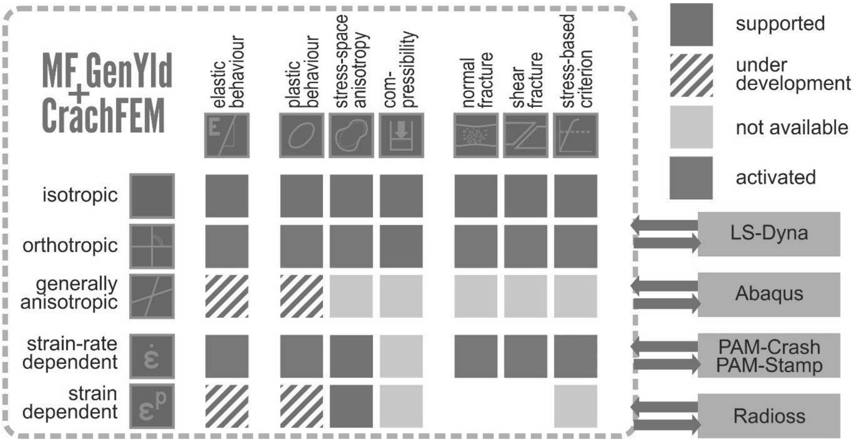


Fig. 3: Modules used for material characterization

A comprehensive test program has been carried out in order to characterize the elastic behavior, hardening behavior and failure behavior. Uniaxial tensile tests with different orientations and at different strain rates have therefore been conducted. Additional compression tests with different orientations, shear tests and biaxial tests have been carried out.

The derived Young's moduli are shown in Figure 4.

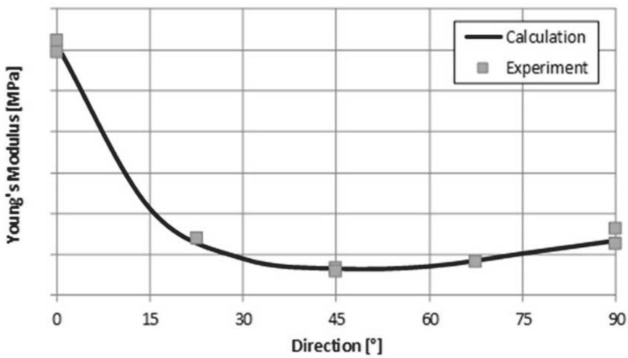


Fig. 4: Directionality of Young's modulus

In the MF-GenYld+CrachFEM material model a reference hardening curve needs to be defined. Usually the symmetry axis with the highest strength is taken as the reference orientation. As this orientation shows the lowest ductility for the investigated material it is necessary to extrapolate the measured hardening curve in a reasonable way. This can be done by using the hardening curve from the orientation which shows the highest ductility. Inside the material model the equivalent plastic strain based on plastic work is used. Strains from individual loading directions must therefore be transformed into the equivalent plastic strain based on plastic work.

The material model enables the use of different orthotropic yield locus definitions. Here the yield loci according to Hill-1948 [2] and Dell-2006 [3] have been used as a basis. It is possible to distinguish between tension and compression behavior. Figure 5 shows the directionality of the yield strength, Figure 6 the directionality of the plastic Poisson's ratio.

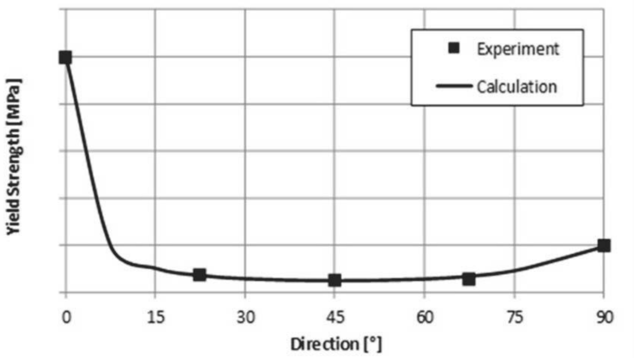


Fig. 5: Directionality of the yield strength

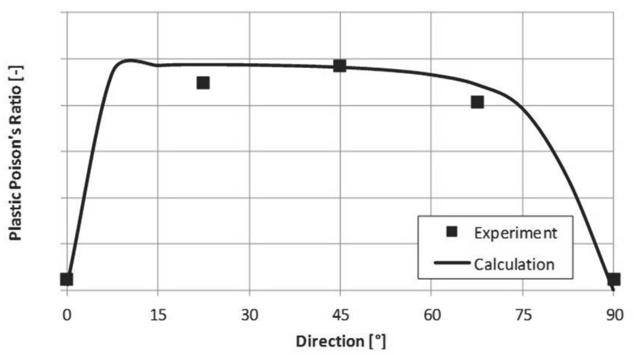


Fig. 6: Directionality of the plastic Poisson's ratio

The hardening behavior of organic sheets can be comparatively high in the fiber directions. In addition, the plastic strain at fracture is usually very low for this direction. Consequently the use of failure criteria which are based purely on plastic strains can cause problems. Very small errors in determining fracture strain can result in serious errors with respect to strength at failure. For this reason a stress-based failure criterion has been developed which also covers the orthotropic behavior of the investigated organic sheet. The orientation-dependent fracture stress is shown in Figure 7.

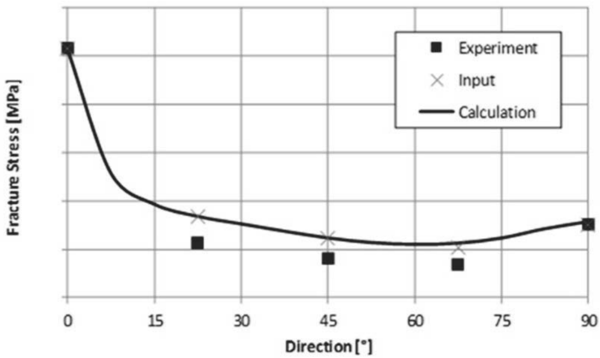


Fig. 7: Directionality of fracture stress based on tensile testing

The fracture locus overestimates the fracture for the orientations at 22.5°, 45° and 67.5°. Tensile tests in these orientations showed a low hardening behavior (schematically shown in Figure 2 for the 45° orientation). Here small errors in defining the fracture stress can lead to large errors for the fracture strain. Due to this problem an additional strain-based failure criterion has been defined which covers the ductile failure modes in the range of orientations away from the fiber orientations.

The stress-based fracture modes do not therefore need to describe the low fracture stresses in the ductile orientations. The combination of the classic strain-based failure model approach in the MF-GenYld+CrachFEM material model and the new stress-based approach seems to be well-suited to describing the complex failure behavior of organic sheets.

3. Current status

In a first step basic specimen tests are simulated with the modified material model and a derived material card. The results for the quasi-static tests in different orientations are shown in Figure 8.

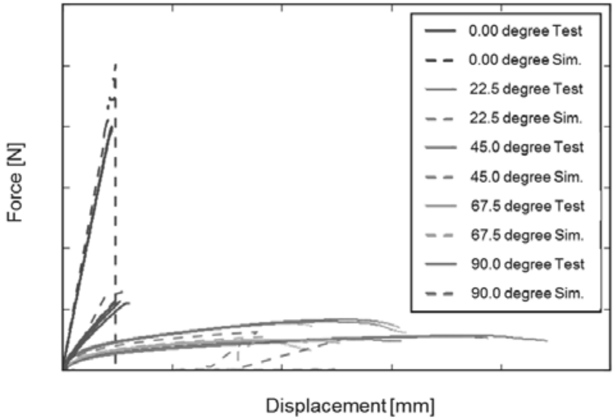


Fig. 8: Simulation of basic specimen forms, uniaxial tension (force-displacement)

This approach covers the strain-rate dependency of the strain-based and stress-based failure modes as well. A comparison between experiment and simulation is shown in Figure 9.

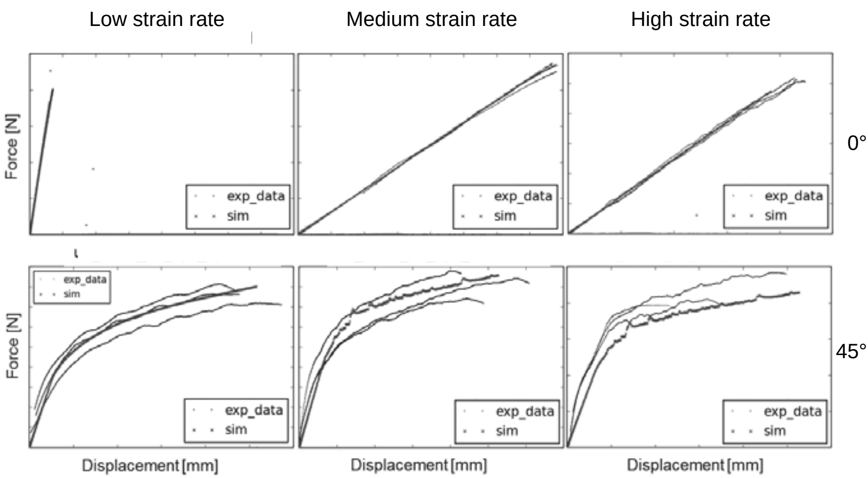


Fig. 9: Simulation of basic specimen forms, uniaxial tension (force-displacement)

In this study the assumption has been made that the material behavior can be described by an orthotropic approach. Current developments of the material model approach are no longer limited to an orthotropic representation. The general anisotropy of elasticity and plasticity can be described either based on the superposition of two or more transversely-isotropic components or on the structural tensors approach [4]. A validation example of the superposition method for initially orthogonal fabric (example without failure criterion) is shown in Figure 10.

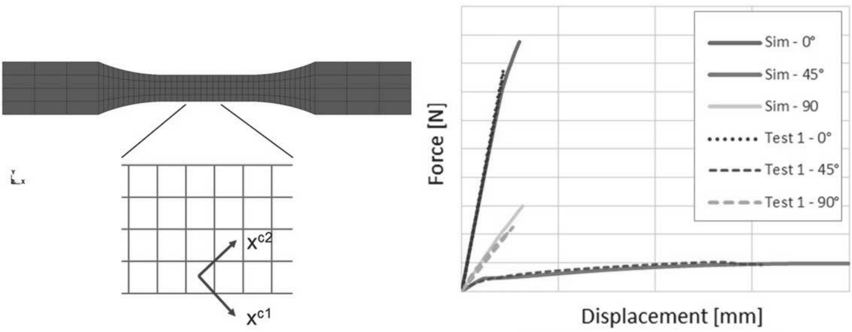


Fig. 10: Force-displacement behavior in the case of the uniaxial tension test

To further validate the new material model, prototype parts have been manufactured with an endless-fiber-reinforced polyamide material and tested in different scenarios, see Figure 11.

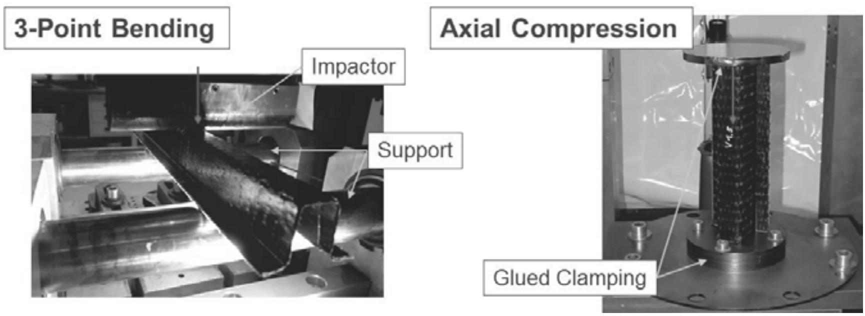


Fig. 11: Prototype parts and load cases for simulation validations

The crash simulations are performed at the Ford Motor Company with the enhanced MF-GenYld+CrachFEM material model supplied by a material card generated by MATFEM and based on advanced physical material tests of this particular endless-fiber-reinforced thermo-plastic.

The validations show a very good correlation when the new material model is used. Figures 12 to 15 show the comparison of simulation and physical tests for quasi-static and dynamic 3-point bending and axial crushing tests.

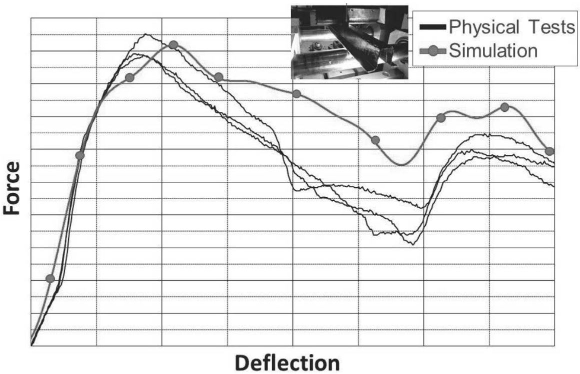


Fig. 12: Crash simulation results vs. test results 3-point bending, quasi-static

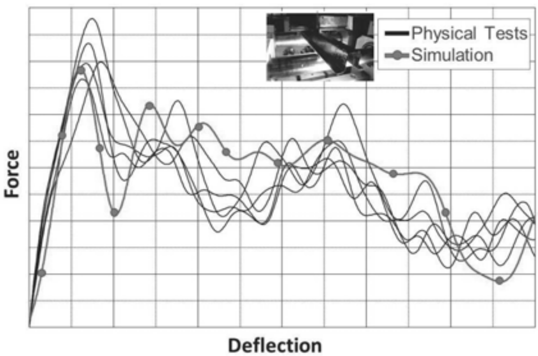


Fig. 13: Crash simulation results vs. test results 3-point bending, dynamic

The results show a very good correlation between simulations and physical tests. The stiffness, yield and fracture behavior of the parts are correctly represented for all load cases and impact velocities, indicating that the developed material model and related material card can correctly predict the complex deformation and failure behavior of organic sheets.

This very good result is only achievable when the geometry is correctly represented in the crash simulation mesh. An element size in the range of 2 mm to 3 mm is used and the local thicknesses must be correctly taken into account.

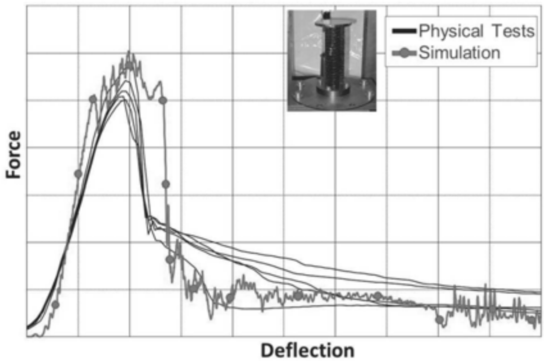


Fig. 14: Crash simulation results vs. test results axial crush, quasi-static

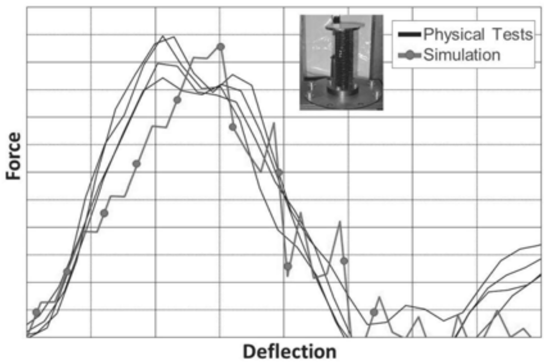


Fig. 15: Crash simulation results vs. test results axial crush, dynamic

4. Future developments

Following the very good crash simulation results with the MF-GenYld+CrachFEM material model for endless-fiber-reinforced thermoplastics, the Ford Motor Company and Kirchhoff Automotive Deutschland GmbH together with MATFEM Partnerschaft Dr. Gese & Oberhofer will work together on the characterization and development of related material cards for additional endless-fiber-reinforced thermoplastic materials to enable the seamless implementation of this promising material group in series production.

In addition, this work is the basis for further material model development for the classic material group of endless-fiber-reinforced thermosets carried out in collaboration between the Ford Research & Innovation Center Aachen and MATFEM Partnerschaft Dr. Gese & Oberhofer.

5. Conclusion

This article shows a possible approach to improved predictability of the FEM simulation of impact-loaded endless-fiber-reinforced thermoplastic parts. Using the MF-GenYld advanced material model in combination with the CrachFEM fracture module a significantly increased accuracy in the deformation and fracture behavior for the analysed endless-fiber-reinforced thermoplastic material can be achieved. The comparison between physical tests and simulation show very good correlation. For this reason the MF-GenYld+CrachFEM advanced material model from MATFEM is in use globally at the Ford Motor Company.

[1] M. Franzen, H. Lanzerath, G. Oberhofer, H. Gese: Problems and possible solutions in finite element simulation of impact loaded plastic parts in interior applications
Aachener Kolloquium 'Fahrzeug- und Motorentechnik' ; 8 - 10 October 2007 Aachen

[2] R. Hill: A theory of the yielding and plastic flow of anisotropic metals. Proceedings of the Royal Society. London, A193 (1948), p 281

[3] H. Dell, H. Gese, G. Oberhofer: Advanced yield loci and anisotropic hardening in the material model Mf GenYld + CrachFEM, Proceedings of the Numisheet 2008 September 1 - 5, 2008, Interlaken, Switzerland

[4] G. Oberhofer, H. Dell, M. Vogler, H. Gese, Current solutions and open challenges in modeling organic sheets, Automotive CAE Grand Challenge, April 12 and 13, 2016

Innovative processing of thermoplastic composites for the Porsche Panamera brake pedal

Continuous-fiber technology for safety components in the vehicle

Dipl.-Ing. **D. Häffelin**, BOGE Rubber & Plastics, Damme

Abstract

For modern vehicle construction the importance of sustainable and economic lightweight design is growing. BOGE Rubber & Plastics faces this task by, among other things, developing a fully automated manufacturing process for continuous-fiber materials for the production of quality-assured cost-effective vehicle systems in relevant numbers with the potential for further increases in volume. Continuous-fiber plastics offer lightweighting potential but until now the process chain has been a long and complex matter to automate. This has so far made it more difficult to use it economically in large-scale production. Taking a safety component as an example, BOGE Rubber & Plastics describes a fully automatic process chain for the production of brake pedals. It begins with plastic pellets and pre-consolidated textile semi-finished products (organo-sheets) and finishes with a brake pedal straight from the mold. The weight saving achieved here in the series process is 40% compared with the conventional pedal made of steel. The present contribution shows the potentials and challenges of material class of continuous fibers, describes the challenges of implementation in the series process, and reveals current process research on series application.

1. Introduction

Generally speaking, the task of lightweight design can be broken down into the three questions regarding

- the right material
- the best shape/design, and
- additional features which can be integrated.

These three questions overlap in the process of component manufacturing, resulting in a finely meshed networking of part design, calculation and material technology.

Regarding the question of the right material, traditional metal designs are being increasingly replaced by polymer solutions, even in primary structures and systems with safety requirements. In addition to the economic advantages of thermoplastics, in many cases the justification is to be found in the favorable ratio between material mechanical properties and density

– in other words, in its potential for lightweighting. This ratio is particularly high with fiber composites especially when

a) the fibers added to the reinforcement run along the direction of loading, and
b) the fibers are long / continuous.

By continuous fibers is meant fibers whose length roughly corresponds to the size of the component and which thus traverse the entire component.

When a material has a higher specific stiffness/strength, a component of the same mass made of this will deform less or will carry a greater load. This relationship is shown in Figure 1. The diagram shows the lightweight potential of continuous glass-fiber-reinforced plastics (GRP) and continuous carbon-fiber-reinforced plastics (CFRP) with regard to specific strength and stiffness as compared with steel and aluminum.

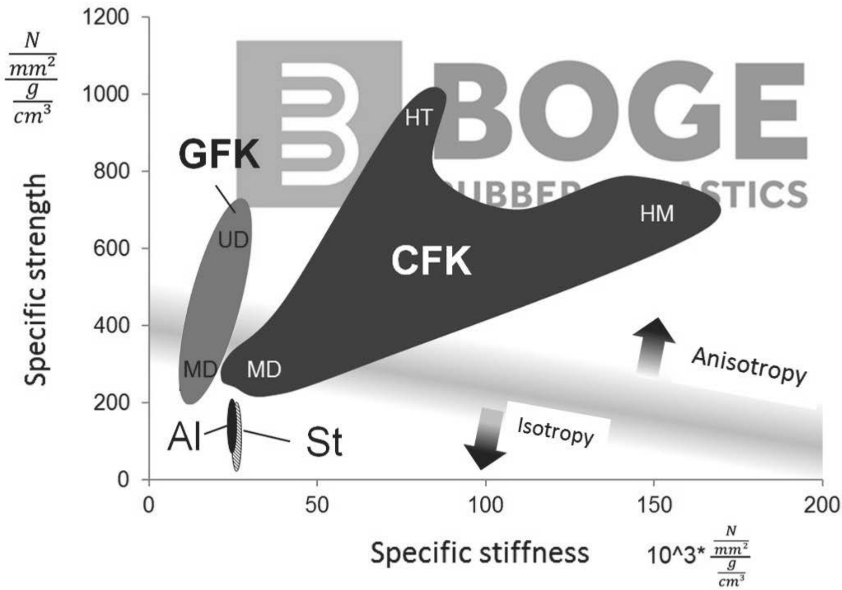


Fig. 1: Lightweighting potential of automotive materials (MD: multi-directional; UD: uni-directional; HT: high tension; HM: high modulus)

The wide spread of mechanical properties is controlled mainly by the fiber architecture. Should the material possess (quasi-) isotropic mechanical material properties (which are not or only a little dependent on direction), the fibers must be incorporated with several orientations in the material (MD or multi-directional fiber orientation in Figure 1). If the fibers are predominantly oriented in one direction (UD or uni-directional fiber orientation) and thus processed, the resulting material will have a strong dependence on direction, that is, the material is anisotropic. The change from an isotropic to an anisotropic material design is accompanied by an increase in lightweighting potential although this increase is only in the fiber direction. A precise knowledge of the load path routes of the target components and also a reduction to a few significant load paths are a basic requirement for designing an anisotropic component using oriented continuous fibers.

This will be the situation for a brake pedal when the underlying case is a bending beam predominantly under torsional loading. If the amounts of bending load and torsional load are known, the fiber amounts for the respective bending or torsional case are calculated analytically in a simplified analytical approach and the continuous fibers layered in accordance with this to create an anisotropic organo-sheet.

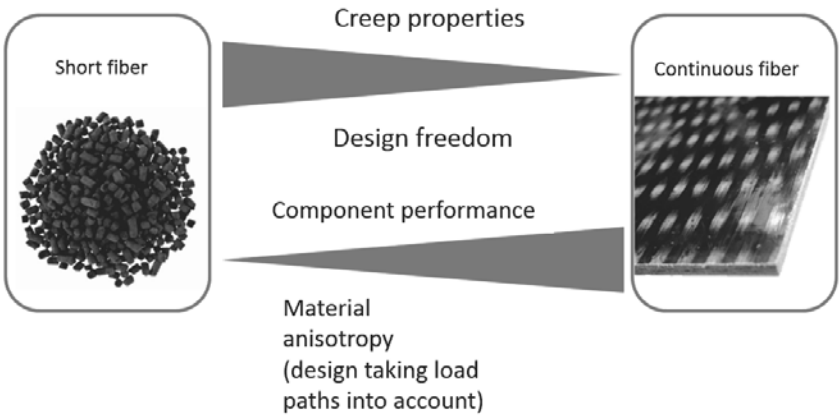


Fig. 2: Mechanical property differences of short-fiber reinforcement and continuous-fiber reinforcement

As even sheet steel cannot be endlessly deep-drawn, neither can continuous-fiber-reinforced materials be shaped in any way whatsoever. Starting with the flat semi-finished sheets supplied (hereinafter organo-sheet and cut sections of this), the material is reshaped three-dimensionally in a forming operation or draping process. Exceeding the shaping limits of the organo-sheet results in defects such as fiber warpage and wrinkles in the material, and as a consequence mechanical properties decrease locally. For this reason, more complex component areas are provided with a short-fiber-reinforced injection-molding compound.

As shown in Figure 2, the injection-molding compound offers a high degree of design freedom, for example, for ribs, supports and other functional areas, but does so at the expense of the specific fiber orientation (anisotropy). Determining which areas will use continuous-fiber material and which will use short-fiber-reinforced material should be assessed against a technical and economic background.

Fig. 3: Pedal system of the Porsche Panamera G2 in continuous-fiber technology

The result of this reconciliation is shown in Figure 3 for the brake pedal of the *Porsche Panamera G2*. The all-plastic brake pedal consists of a main body formed by a continuous U-profile, downwardly open, made of continuous fibers. Short-fiber-reinforced plastic is used for the foot plate, bearing point, ribs and a top-mounted safety element. The surface of the continuous-fiber section is smooth, shiny, and closed. The component comes from a fully automated production cell with no subsequent surface finishing.

2. Component development

Supplemented by the choice of glass fibers in the continuous-fiber- and short-fiber-reinforcement and also polyamide as the matrix, the selection of material is completed. The geometry/shape of the component, on the other hand, has not yet been decided and this must be done next.

Short-fiber-reinforced and continuous-fiber-reinforced thermoplastics span a range of strength and stiffness values within which the geometry of the brake pedal is predimensioned. Together with the length of bending / torsion beam and the loads to be transferred, an estimate can be made of the component with regard to wall thicknesses and installation space requirements. The analytically estimated lay-up structure mentioned above is also input here. In the conceptualization process, the constraints of the manufacturing process and also visual aspects give rise to the component concept shown in Figure 3 (downwardly open shell with downwardly extended stiffening ribs) .

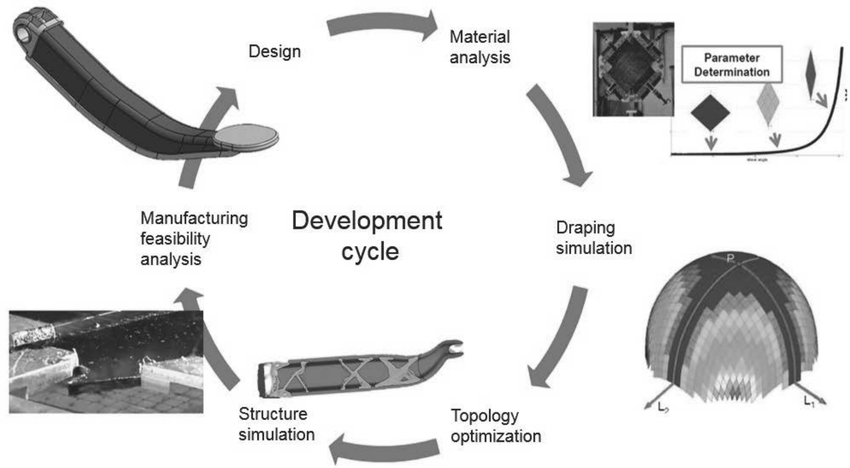


Fig. 4: Development cycle for a component with continuous-fiber reinforcement

Once the initial design is available and computer-aided isotropic stress-field modeling has been completed, areas of higher stress can be identified and the level and direction of stress assigned. Component areas with high stress in predominantly the same direction mark the potential application for the continuous-fiber materials. Furthermore, the layered structure of the continuous fibers can be more precisely dimensioned with the aid of information regarding the stress level and the division into tensile / compressive shear stresses.

What has been available up to this point is an initial dimensioning of the component, the lay-up of the continuous-fiber material and the wall thicknesses. Even at this early stage of development, it is advisable to check the geometry of the organo-sheet sheet shell to see whether it is possible to reshape the fibers – in other words, drape the organo-sheet – without defects arising. This question can be approached through computer-aided modeling or experimentally. In the experimental check, a comparable fiber architecture is placed on a model core and an assessment made of both the material behavior during the placement procedure and also the draping result.

In the computer-aided modeling approach, the simplest case is a kinematic draping simulation of the geometry which is reconciled with the critical shear angles of the fiber material. If material-specific characteristic values are available, draping in interaction with the influence of the mold can be optimized in a further FE simulation . If the component geometry of the continuous-fiber shell is appropriate for fibers, the geometry of the injection-molding component will be determined. On the basis of computer-aided optimization methods for the component topology which take into account the continuous-fiber content, within the procedure an arrangement of structural components (accumulation of volume elements) is suggested which the designer can follow by targeted positioning of the ribs and stiffening elements. This will always involve an interpretation on the part of the designer. The design loop will continue with the assessment of component mechanics. Here the model, now equipped with ribs, is analyzed numerically, taking into account

- the anisotropic continuous-fiber shell, and
- the fiber orientation of the short-fiber sections which arises from the filling.

In the manufacturing feasibility analysis, mold and installation concepts are set up and cycle times estimated. Once the design meets all mechanical / visual and economic requirements, the loop is broken. Should deviations arise, a further cycle will be run.

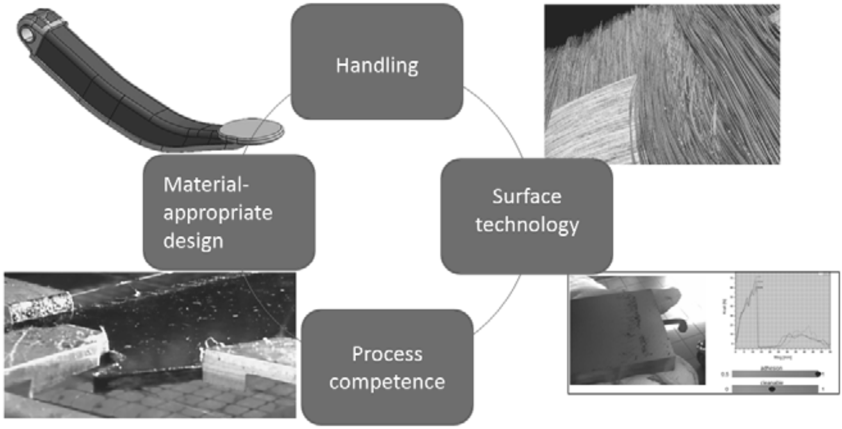
3. Process development

A necessary condition of cost-effective component production is end-to-end automation in the processing of fiber composites in high quantities. In the context of continuous-fiber processing of pre-consolidated, thermoplastic fiber semi-finished products, the process tasks are:

- Cutting the organo-sheets into component-specific inserts
- Heating these continuous-fiber blanks up to molding temperature
- Forming / draping
- Re-consolidating the draped organo-sheet blanks to final wall thickness
- Hybridizing with short-fiber-reinforced injection-molding compound by flooding or molding-on.

The process begins with the organo-sheet. Delivered by the supplier as component-specific blanks, they can be input into the BOGE system. Handling the blanks before they are heated

is not a critical matter since they have a smooth and gas-tight surface. It is however a different matter when the organo-sheet is heated above the melting point of the matrix.
The processing stresses in the textile in the organo-sheet which are introduced during production relax and this causes an increase in the wall thickness. In this state, the organo-sheet behaves in a similar way to a hot, wet towel. Particularly during the heating and forming processes, mechanical action must be applied to the fibers in order to hold them and bring them into shape.



Fig, 5: Areas of competence in processing

Once the thermoforming temperature has been reached, the material is moldable, the fibers can be pushed together, the surface is textured and wetted with viscous matrix. In this state, handling the material in a manner appropriate to the fibers can be of crucial importance. Wrinkles, fiber breaks or the separation of fiber bundles are common defects which may occur . Even choosing the right substrate during heating of the organo-sheet and the way in which the organo-sheet is held or fixed are decisive factors influencing the later appearance and mechanical properties of the component. The textile's surface wetted with matrix can result in deposition occurring in the process (on the oven and forming tool). With an automated process this deposits must not build up and lead to malfunctions. A correct selection of the surface being handled, be this for suction devices, tool coatings or other fixation equipment, is an influencing factor here.
The field of process competence (Figure 5) describes a large number of factors that are important for the cost-effectiveness of the processing chain. The heating rates and control chains of the oven, the cooling rates of the heated organo-sheets, transportation times, form-

ing speed, mold temperatures, re-consolidation pressures and locking forces during encapsulation must be estimated and the system technology adjusted accordingly.

Since the use of this composite material is relatively new, some models may be inaccurate for dimensioning or be based on inaccurate assumptions. An improvement and refinement of these models improves the development process and will in future lead to a design of component and process which comes closer to intentions, and thus results in further weight reductions.

A material-appropriate geometry of the continuous-fiber portion does not end with successful conclusion of a draping analysis which gives the go-ahead for its incorporation in the component geometry. In particular, the detailed design of edges and forming radii has an influence on the local fiber volume content, demoldability / absorptive quality of the shell, binding of the melt, and deposits in the mold.

The areas of processing competence shown do once again indicate the closely meshed networking between materials technology, part design, tool engineering and calculation, and justify the also closely meshed networking within the interdisciplinary development teams working on continuous-fiber components.

The individual components of the process design are integrated into the central process. Two variants are known in the processing of organo-sheets: a one-stage process and a two-stage process. The two are compared in Figure 6. Both processing variants begin with the organo-sheet being heated to molding temperature; in both processes, the hot organo-sheet is fed into the thermoforming tool and in both processes the forming is effected by the closing movement of the tool. In the one-stage process (Figure 6 top), unlike the two-stage process, the organo-sheet does not entirely fill the mold cavity. Areas are left which will be filled with short-fiber-reinforced injection-molding compound immediately the mold closes.

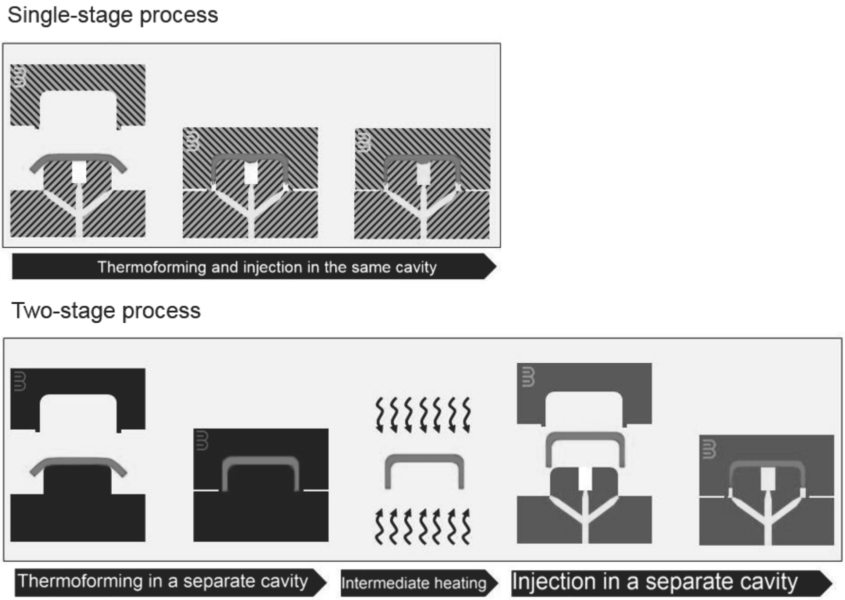


Fig. 6: Difference between the single-stage and the two-stage manufacturing process

In the case of a two-stage process, on the other hand (Figure 6 bottom), two molds are required: one for shaping the organo-sheet and one for molding-on short-fiber reinforcements. This raises the question as to why a two-stage process is used when the single-stage process needs one less mold and the process chain is shorter. The answer is to be found in

- the surface quality required
- the course of the fiber in the area of T joints
- the edge design

of the component. The difference in the surface quality is shown in Figure 7. The image corresponding to the single-stage process shows the low level of matrix filling between the fiber bundles due to the low matrix pressure during re-consolidation. In the single-stage process, the hot organo-sheet is shaped by a core which is already provided with ribbed areas. If the organo-sheet is now compressed to the final wall thickness of the component, the plastic matrix in the textile will not be fully enclosed and will follow the path of least flow resistance into the open ribbing area.

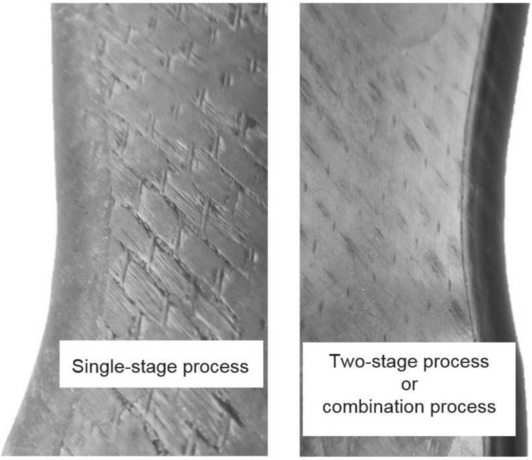


Fig. 7: Effect of process selection on the component surface

The matrix pressure required for reproducing the final surface is not reached or maintained, and the frontal flow into the ribbing area deforms the fiber layers over rib width, as shown in Figure 8 .

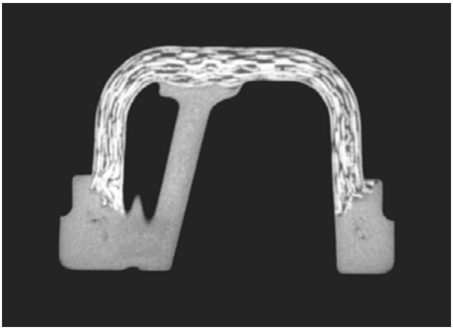


Fig. 8: CT analysis of the fiber path in the one-step process

In many cases this is technically acceptable, especially when the molded-on shape is thin or when no surface requirements or at least only minor ones have to be met.
Separation into two cavities does, however, make it possible for the organo-sheet to be precisely shaped even in those areas to be subsequently backfilled with injection-molding com-

pound. For this purpose a second cavity is required which shapes the organo-sheet within a filled and enclosed volume. It is, accordingly, possible to give the edge area a subsequent undercut in the organic sheet, or to integrate edge trimming in the shaping of the organo-sheet.

BOGE Rubber & Plastics has now developed an intermediate process or combination process in order to combine the economic potential of the single-stage process with the component quality of the two-stage process . Here, at every opening of the press a component is created off the mold (single-stage process) from a tool with two cavities (two-stage process). The starting point here is the two-stage process, whose processing steps are rearranged, as shown in Figure 9.

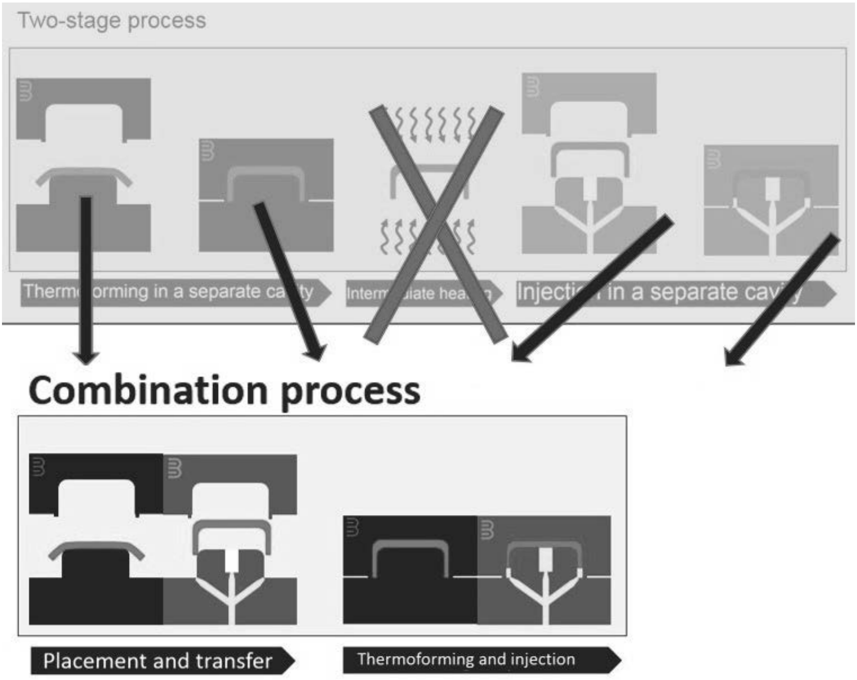


Fig. 9: Arrangement in the combination process

The basic condition for this combination process is the edge design of the reshaped organo-sheet in the forming tool. If subsequent edge trimming of the shaped organo-sheet is not required, it can be removed when still hot and placed in the injection cavity for further processing.

The sequence is described below, on the basis of the schematic depiction of the tool in Figure 9. On the left-hand side (black) the plasticized organo-sheet blank is inserted for forming / draping. When the mold closes, the blank is formed into a U profile, compressed to final wall thickness while the matrix pressure is built up and maintained by the full closure of the cavity. The profile so formed cools down to mold temperature and solidifies. In this kind of arrangement, the temperature of the thermoforming mold takes on a double importance. It influences the shaping of the organo-sheet shell and determines the temperature of the demolded continuous-fiber profile whose surface the melt meets.

When the mold opens, the U profile is automatically removed and shifted to the adjacent cavity. At the same time the next hot organo-sheet blank is placed in the first cavity. When the mold closes again, the short-fiber-reinforced thermoplastic melt comes up against the U profile and firmly bonds to it. While this is going on, the next continuous-fiber profile is being shaped in the thermoforming cavity. The next time the mold opens, the following actions take place simultaneously: a hot organo-sheet is fed in, the shaped continuous-fiber profile is thermoformed and a finished component is removed . This final process repeats until the end of production. The state-of-the-art process step of intermediate heating in the two-stage process is omitted, the process chain can be entirely automated, the advantages of a two-stage process with respect to detailed design and surface characteristics are combined with the economic advantages of a single-stage process, the process chain is shortened.

References

1. **VEREIN DEUTSCHER INGENIEURE.** Entwicklung von Bauteilen aus Faser-Kunststoff-Verbund Grundlagen. [Buchverf.] VDI-Gesellschaft Kunststofftechnik. Düsseldorf: VDI, 1989.

2. Kamphaus, T., Wagener, K. und Rogowski, W. *DE 10 2013 206 647 A1* DE, 16.10.2014.

3. *Thermoplastische Composite Hybridbauteile.* **Lutter, F., Willms, P. und Brandt, M.** Fortschritte in der Kunststofftechnik : FH Osnabrück, 2015. Lanxess Deutschland GmbH.

4. **Bel, S. et al.** Finite element model for NCF composite reinforcement preforming: importance of inter-ply sliding. *Composites: Part A.* Part A 43 (2012) 2269-2277, 2012.

5. **Biermann, D., Hufenbach, W. und Seliger, G.** *Serientaugliche Bearbeitung und Handhabung moderner faserverstärkter Hochleistungswerkstoffe.* Dresden : Technische Universität Dresden, 2008.

6. **Reuter, W.** Hochleistungs-Faserkunststoff-Verbunde mit Class-A-Oberflächenqualität für den Einsatz in der Fahrzeugaussenhaut. Kaiserslautern: Institut für Verbundwerkstoffe GmbH, 2001. ISBN-3-934930-15-8.

7. **Beutler, O.** Fertigung des Organoblechbremspedals. *Porsche Opening.* DAMME : BOGE Rubber & Plastics , 2015. vol. Presentation.

Energy-efficient production of thermoplastic CFRP parts by one-step direct processing

Dr.-Ing. **J. Reddemann**, Dr.-Ing. **H. Seifert**, AUDI AG, Ingolstadt

Abstract

Continuous-fiber-reinforced plastics have so far in the automotive industry been used mainly in areas of application involving small production quantities. Reasons for this include the very long cycle times of thermoset matrix systems as well as the associated high level of manual work involved in production. In contrast, thermoplastic fiber composites offer the possibility, via automated process routes, of producing even larger quantities economically. However, the energy required to produce fiber-reinforced plastic components has until now remained very high, irrespective of the matrix system used, which means that in a holistic assessment the weight advantage can rarely compensate for the additional energy consumed in the manufacturing phase. It is however possible to further reduce this energy consumption in the manufacturing phases by integrating several process steps in a single mold.

1. Introduction

Ever stricter environmental regulations and increasing crash-related requirements have resulted in lightweight construction in the automobile becoming increasingly important in the past in the development of new vehicles. Here fiber-reinforced plastics can score over conventional lightweight materials, especially in offering great freedom of design coupled with high specific strength and stiffness values. Depending on the application, lightweighting with carbon fiber can mean weight savings up to 80% as compared with steel and up to 50% as compared with aluminum [2].

The current utilization of fiber composites in automotive engineering has however so far been limited mainly to series produced in small numbers. High production costs due to long cycle times and energy-intensive process routes as well as the high price of the raw material carbon fiber are common reasons for declining to use fiber-composite plastics in high-volume production. This means that if a higher proportion of fiber-composite plastics is to be used in automobile manufacturing, improvements in the process technologies and the development of new process routes for producing fiber-composite components will be absolutely essential [1, 3, 4].

In the wake of ever more stringent CO_2 legislation and the concomitant trend towards electromobility the weight alone of the vehicle will in future no longer be central in representing the environmental impact. When the holistic environmental footprint of a vehicle (also known as the life cycle assessment or LCA) is considered, it becomes clear that for a compact-class vehicle with a conventional gasoline engine and a mileage of 200,000 km, about 80% of the CO_2 emissions are attributable to vehicle utilization and about 20% to production of the vehicle (Figure 1). On the other hand, in the case of a battery-electric vehicle (BEV) which runs on power from renewable sources, 95% of the CO_2 emissions occur in the production phase and only about 5% in actual operation of the vehicle [5].

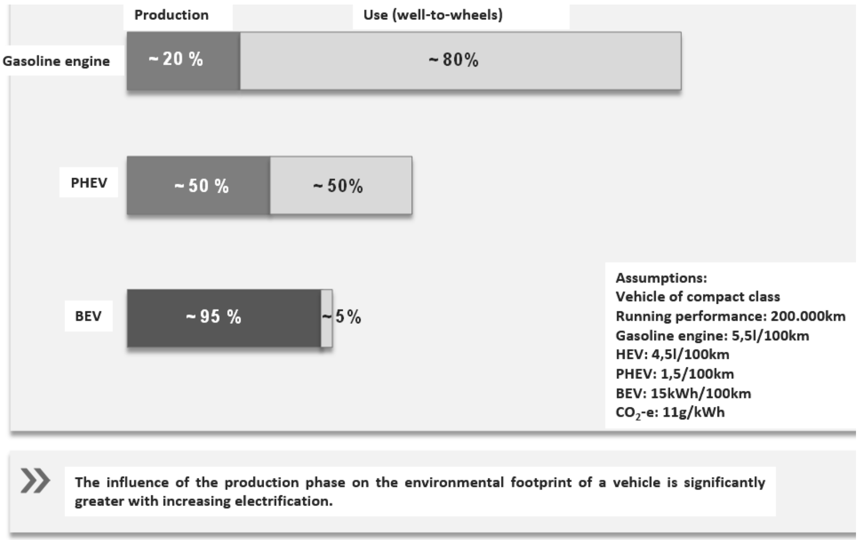


Fig. 1: Proportion of CO_2 emissions with different drive concepts [5]

This comparison makes it clear that with an increasing level of vehicle electrification the focus is no longer on just the weight of the vehicle but also the efficiency of the vehicle production processes moves into the foreground as well. It is therefore all the more important for future vehicle projects to make the corresponding manufacturing processes energy-efficient. One approach to improving energy efficiency in the production of fiber-reinforced plastic components is the so-called in-mold impregnation method.

2. The in-mold impregnation process

Research was carried out into the in-mold impregnation process at Neue Materialien Fürth GmbH in collaboration with the Chair of Polymer Engineering at the Friedrich-Alexander-Universität Erlangen-Nürnberg as part of a 'CFRP high-volume production' project funded by the Bavarian Ministry of Economic Affairs and in 2012 it received the AVK innovation award.

Combining the processes of heating, impregnation and forming into a single process step yielded various advantages over the established multiple-step manufacturing process. Separate production of the prepregs followed by the forming step has until now required repeated heating of the materials used. Combining all of these steps in a single mold has resulted not only in a reduction in energy requirements during production but also in a shorter cycle time. Furthermore, the dry fibers can be arranged appropriately for the stresses they experience, which means a marked increase in design freedom [1, 6, 7].

The high viscosity of the thermoplastic melt requires a sufficiently high temperature during the whole impregnation phase if the matrix is not to freeze prematurely. For one-step procedures this can be guaranteed by a variothermal temperature control of the mold, or by direct heating of the fibers, or by a combination of both variants [2]. To maintain the temperature, in the in-mold impregnation method the heat is generated directly in the reinforcing fibers. Here the electrical resistance of the carbon fibers is exploited to generate heat. When an electric current is applied, due to their ohmic resistance the carbon fibers heat up within a few seconds to a target temperature at which a steady state is reached. This state depends among other things on the current strength and the geometry of the textile structure. [1]

Figure 2 shows the individual process steps of the in-mold impregnation process. First of all, the dry semi-finished fiber product is inserted into the cavity of the injection mold (Step 1). The mold is then closed and the fiber prepreg held in position by a spring-loaded shearing edge. In Steps 1 and 2 the mold is not yet completely closed, which means that initially there is still a compression gap within the cavity. Contact strips are integrated in the spring-loaded shearing edge to allow electric current to be input into the fiber prepreg. In Step 2 electric current is introduced via the contact strips into the fiber prepreg and the electrical resistance of the carbon fibers results in the textile prepreg being heated up to a target temperature which ideally falls within the processing range of the thermoplastic matrix.

As soon as this target temperature is reached and a steady state establishes itself, the injection unit fills the compression gap with matrix material. This starts off slowly and at a low injection pressure so as not to interfere with the fiber orientation in the fiber prepreg and to prevent the matrix from already penetrating the prepreg. Once the compression gap is entirely filled with the specified amount of injected material, the cavity is fully closed by the locking force of the injection mold (Step 3). This causes the thermoplastic melt to infiltrate the fiber prepreg in the direction of its thickness and, with a constant pressure being maintained via the clamping force, the reinforcing fibers are impregnated with matrix.

At the end of the compression phase, the current is turned off in Step 4 and the component allowed to cool down to the demolding temperature for the plastic matrix. The mold can now be opened and the finished impregnated component removed [1].

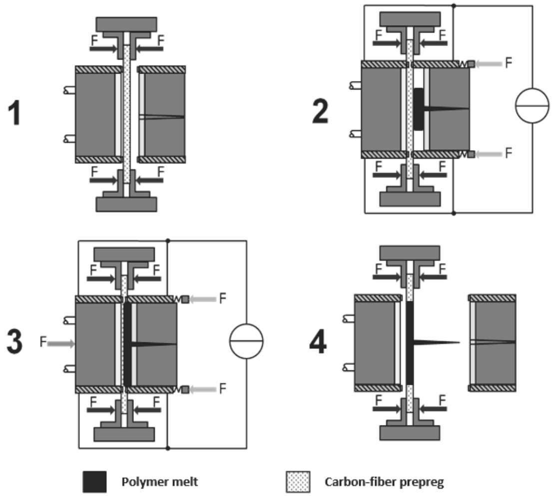


Fig. 2: Schematic representation of the process steps in the in-mold-impregnation process according to [6]

Figure 3 shows the process sequence of in-mold impregnation as a function of time. The current strength and the duration of the power supply are here two important new variables in injection-molding technology for the entire production process. A defined starting time can also be selected for the compression stroke which means that compression can be commenced even during the injection process.

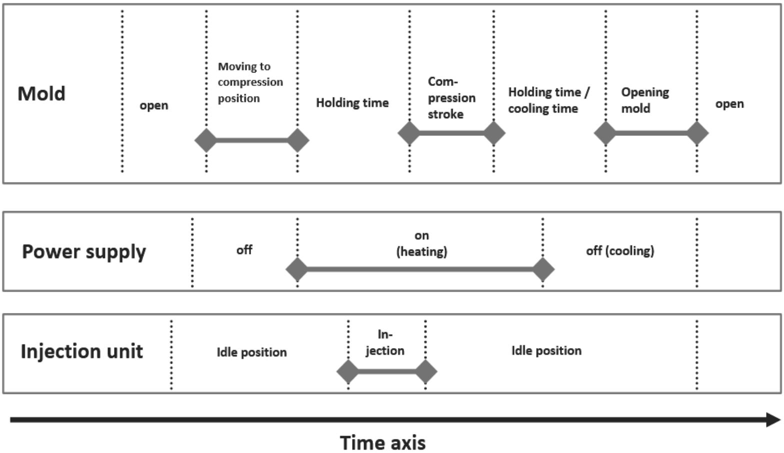


Fig. 3: Process sequence during in-mold impregnation as a function of time [1]

2. Production of test pieces

Textile structures, which exhibit marked inhomogeneities during resistance heating, were impregnated with thermoplastic in order to study the influence of resistance heating on impregnation quality in the in-mold-impregnation process. They were produced in a test-piece mold at Neue Materialien Fürth GmbH (see Figure 4).

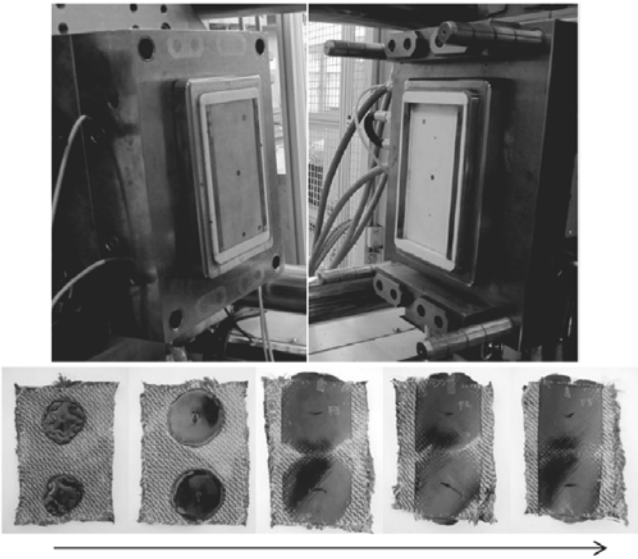


Fig. 4: Test-piece mold installed in an injection-molding machine, and a filling study of the in-mold impregnation process [1]

We now take as an example investigations into a two-ply lay-up with parallel layers of +45°/+45° and also the alternating lay-up of +45°/-45°. The infrared image already shows strongly inhomogeneous heating over the surface. Figure 5 shows temperature distribution at the surface in an infrared image taken in a heating test rig. During the application of current, the carbon fibers which are not connected to the current remain completely cold.

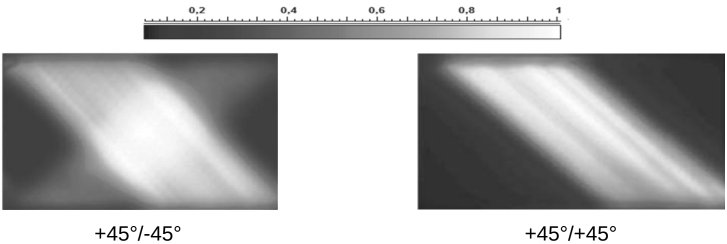


Fig. 5: Relative surface temperature of two-ply textile structures under resistance heating (electrical connection along the long sides) [1]

Figure 6 shows the temperature curve of a thermocouple between the two layers. Immediately the compression phase begins, a marked decrease in temperature occurs. This is in particular due to the change in temperature distribution in the heated non-woven fabric under pressure. As soon as pressure is applied to the multiple layer structure, the temperature differences during resistance heating equalize. The absolute temperature over the entire surface of the heated prepreg drops accordingly. In addition to this, under pressure a greater proportion of heat is transferred into the mold cavity [1].

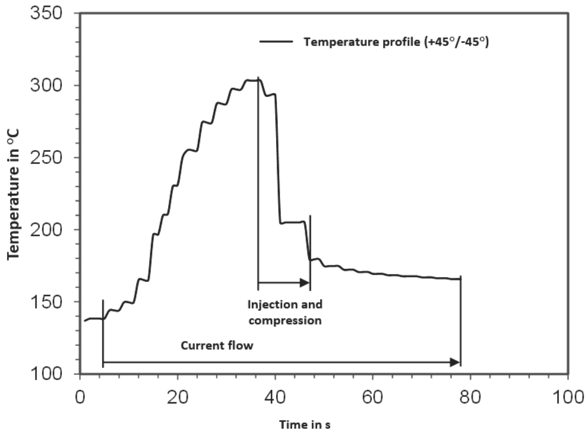


Fig. 6: Time / temperature curve with a (+45°/-45°) lay-up and 30 s current flow at the end of the compression phase; thermocouple between the two layers [1]

A micrograph analysis of the test piece produced reveals a significantly more homogeneous impregnation in the case of the +45°/-45° structure as compared with the +45°/+45° structure. In the case of the +45°/+45° structure, numerous dry carbon fibers can be seen on the rearside of the sheets at a distance from the gate (Figure 7). The area with dry carbon fibers also matches the cold areas occurring during resistance heating in heating tests. Temperature differences which already occur during resistance heating of the dry fibers and which under compressive loading are not evened out, in the investigated structures result in these differences also being found in the impregnation quality of the sheets produced.

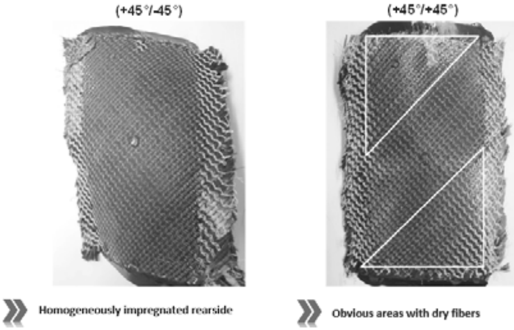


Fig. 7: Back of the impregnated test pieces, with areas of dry fiber marked [1]

It becomes clear when calculating the power used to heat the textile structures that with multiple ply lay-ups much less power is required to reach similar maximum temperatures provided the lay-up has been competently designed (example: +45°/-45°). Figure 8 demonstrates this via a comparison of the single-ply and two-ply structures. Provided the average temperatures suffice for complete impregnation of the component, energy can also be saved by the lay-up design.

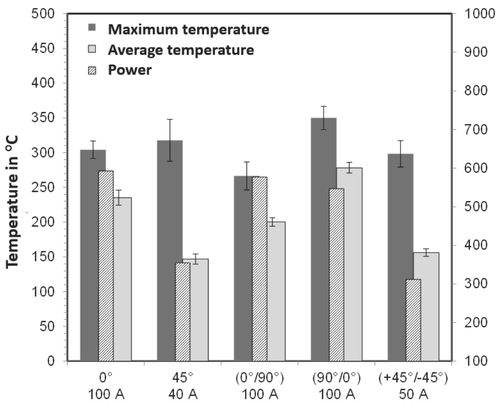
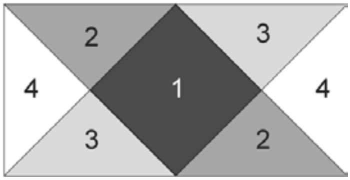


Fig. 8: Maximum temperature, average temperature and heating power in the heating test rig for single- and two-ply structures [1]

A thermographic analysis of the resistance heating is not possible directly in the injection mold, which meant that the temperature distribution of the different plies was mapped using a simulation model in ABAQUS® . Table 1 shows a comparison of the simulated temperatures of a +45°/-45° layer structure. Similarly to the heating tests, the lower +45° layer shows through on the surface of the top -45° layer, which results in four different temperature areas. The simulation model which was developed already shows a very good agreement with the experiments and can thus also be used for predicting the temperature distribution of more complex layered structures. [1]

Table 1: Comparison of the individual temperatures of the +45°/-45° variant (no pressure) [1]



	Area 1 in °C	Area 2 in °C	Area 3 in °C	Area 4 in °C
Test	267 – 317	207 – 247	127 – 147	42 – 67
Simulation	287 – 309	232 – 284	157 – 192	40 – 67

3. Summary

Basic research into in-mold impregnation has shown that it is possible to combine the process steps of heating, forming and impregnation in a single mold in a conventional injection-molding machine. Even dispensing with the intermediate process of producing the prepreg means a considerable reduction in energy consumption. In addition, electrical resistance heating as compared with conventional heating methods involves very low losses and an efficiency of almost 99% [1]. The heat can be introduced by the intrinsic heating technique directly where it is needed. Initial simulation models offer the in-mold impregnation method the possibility of predicting impregnation quality in the finished component with the aid of the temperature distribution.

As part of the 'TC-Fast: energy-efficient rapid processing of carbon-fiber-reinforced thermoplastics' joint project funded by the Federal Ministry for Economic Affairs and Energy, running from 01.07.2016 to 30.06.2019, further investigations are being conducted into the in-mold impregnation process with a view to further process optimizations. With an appropriate process maturity. the actual energy savings can then, for example, be directly compared with the conventional production of organo-sheets. In addition to the advantages in terms of energy efficiency, the greater freedom of design arising from dry draping of the carbon fibers should also be taken into consideration. Further geometries and demonstrators are also being examined as part of the joint project.

References

[1] Reddemann, J: Beitrag zum energieeffizienten Einsatz von Thermoplast-CFK im Automobilbau, Dissertation Universität Erlangen-Nürnberg 2016

[2] Neitzel, M.; Mitschang, P.; Breuer, U.: Handbuch Verbundwerkstoffe: Werkstoffe, Verarbeitung, Anwendung. 2nd edition. Carl Hanser Verlag, Munich 2014

[3] Lässig, R.; Eisenhut, M.; Mathias, A.; Schulte, R, et al.: Serienproduktion von hochfesten Faserverbundbauteilen: Perspektiven für den deutschen Maschinen- und Anlagenbau. Roland Berger Strategy Consultants 2012, http://lightweight.vdma.org/documents/266675/2307595/Roland-Berger-Studie_CT_2012 (20.11.2016)

[4] Holschuh, R.; Becker, D.; Mitschang, P.: Verfahrenskombination für mehr Wirtschaftlichkeit des FVK-Einsatzes im Automobilbau, lightweightdesign (2012), 04, pp. 14–19.

[5] Heil, U.: LCA - Eine Methode zur nachhaltigen Produktentwicklung, VDI Kunststoffe im Automobilbau (2015), pp. 221–232.

[6] Müller, T.; Drummer, D.; Linn, C.; Hoffmann, L.: Ein energieeffizientes Verfahren für den Leichtbau, Kunststoffe 102 (2012), 6, pp. 70–73.

[7] Linn, C.; Hoffmann, L.; Müller, T.; Drummer, D.: Herstellung von CFK-Bauteilen durch Direktimprägnierung mit Thermoplasten in der Spritzgießmaschine, lightweightdesign (2012), 3, pp. 56–61.

3-D direct deposition of reinforcement fibers in the fiber blowing process

State of the art in natural fiber processing

R. Korn, M.Sc., BMW AG (via AlphaKraft GmbH), Munich;
Dr.-Ing. **T. Reußmann,** TITK e.V., Rudolstadt

Natural-fiber-reinforced plastics (NFP) are interesting lightweight materials and are used primarily in the automotive industry in the manufacture of interior trim parts (instrument panels, door beams, side panels). Component manufacturing takes place in a multi-stage process:

1. Making the semi-finished product (production of fiber mats)
2. Making the component (compression molding of fiber composites)

During manufacture of the semi-finished products in the textile industry, the natural fibers are opened up, mixed and made into fiber mats by aerodynamic laying-down of the non-woven material or by carding. These natural fiber mats can be cut to size by the non-woven manufacturer and supplied as finished blanks.
The plastics industry handles the manufacture of the component, which is normally done by compression molding. Here, depending on the matrix material used, a distinction is drawn between thermoset and thermoplastic natural-fiber composites. In comparison with other technologies such as, for example, injection molding, compression molding has a number of disadvantages:

- Variable component thicknesses are not possible
- Reinforcing ribs are not possible
- Fiber mats can only be reshaped to a limited extent
- 10-20% cutting waste in the manufacture of the component
- Load-appropriate dimensioning is only conditionally possible
- Low flexibility in mat production.

International competition forces manufacturers to further streamline processes, to reduce the weight of the component, to integrate reinforcement elements and add-on parts, and also to save material costs at the same time as ensuring global availability. This also applies to the production of natural-fiber-reinforced plastic components. Conventional mat technology sets limits here.

Fiber-blowing 3D contours

Fiber-blowing is a new technology from the textiles sector by which fibers of finite length from the short cut to an average fiber length of 80-100 mm can be processed directly. The fiber material is transported by means of an air stream and injected into an air-permeable mold (blow-in mold) thereby filling it. With an admixture of thermoplastic binding fibers the bonded fiber fabric can then be solidified by thermal action. This results in a 3D preform of accurate contours, which can be physically handled and is available for further use. The main advantages of this procedure are:

- Saving of process steps
- Possibility of making three-dimensional component shapes
- Requirement-specific component cross-sections
- Reduction in production waste

This method has only a few process steps and offers many degrees of freedom with regard to use of the fiber material and the molded-part geometry which can be produced. Depending on the intended application and the part numbers required

- sliding-table machines (for low production series and on pilot plant scale)
- rotary-table machines (for series applications)

can be used. The following diagram, Figure 1, illustrates the operating principle.

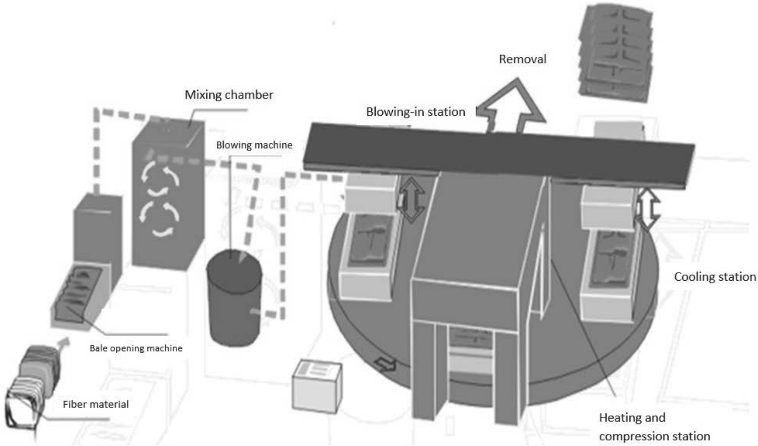


Fig. 1: Fiber-blowing system operating on the rotary table principle [1]

The fibers are first opened up, mixed and fed into the fiber feeders. Following a program sequence controlled by a PLC, the feeders send the fiber mixture to the blowing machine, which inputs it under pneumatic pressure into a ring circuit at the blow-in mold. Different thicknesses can be set at the blow-in mold via the vertical travel of the blowing-in station. Program-controlled blower nozzles blow in the fiber material. Excess fibers (for instance, at the moment when the mold is completely full) are taken via the ring circuit back to storage where they are ready for the next filling operation.

During the thermal solidification process which follows, the fiber 'cake' formed in the blow-in mold is moved to the heating and compression station, compacted there, hot air is passed over it and then it is compressed while cooling. Here the degree of compaction can be set to requirements. After cooling, the mold is opened and the 3D fiber preform removed.

Application of the fiber-blowing process to the production of composites

On the basis of the advantages of the fiber-blowing process, this technology also appears of interest for the production of highly compressed composites. Compared to the mat technology, with 3D fiber blowing the process chain can be shortened significantly by dispensing with the production of semi-finished material: fiber material is blown directly into a temperature-controlled, contoured, three-dimensional mold and then compressed at high pressure (see Figure 2).

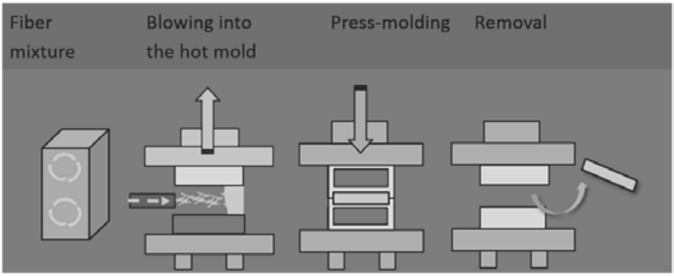


Fig. 2: Schematic of the process sequence in composite production [2]

In order to be able to assess the potential of this technology, fundamental studies into the production of fiber-reinforced plastic components by the 3D fiber-blowing method were carried out at TITK in collaboration with its industrial partners Yanfeng Automotive Interiors, SGL Automotive Carbon Fibers GmbH & Co KG and the BMW Group. The following challenges needed to be solved:

- Optimization of material composition
- Tooling and mold-making
- 3D deposition in the blowing-in station with precise conformation to contours
- Fast transfer into the press
- Short cycle times with low energy consumption.

In addition to the development and qualification of the 3D fiber-blowing method for the direct manufacture of composite components, there were additional project objectives associated with the demand for lightweight solutions in the automotive industry:

1. Reduction of component weight
2. Optimization of mechanical properties by the addition of secondary carbon fibers (sCF).

Machine technology and test materials

A pilot plant made by Robert Bürkle GmbH was available at TITK for 3D fiber blowing. This system has a table size of 2.20 x 1.50 m with a maximum molding pressure of 2000 kN and is thus suitable for the production not only of low-density insulation parts but also of hard composites (Figures 3 and 4).

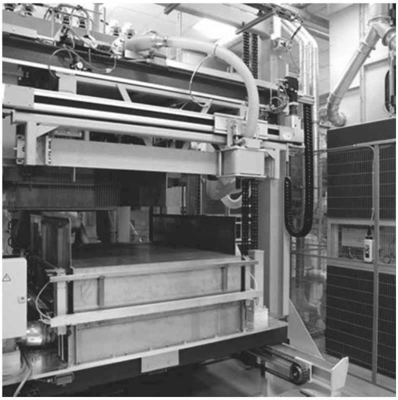


Fig. 3: Blowing-in station and blow-in mold

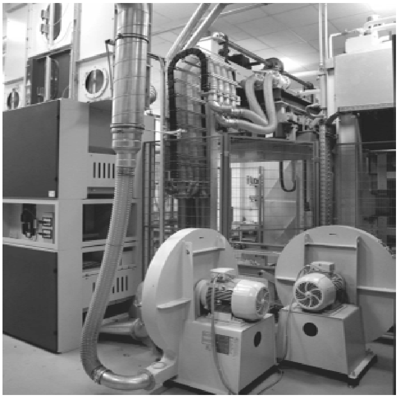


Fig. 4: Fiber storage and blowing machines

Wood fibers bonded with Acrodur were used as the starting material for investigations into producing natural-fiber composite parts. This fiber material is used at the Yanfeng Automotive Interiors company for making wood-fiber mats and is used in series production by various automobile manufacturers. For the thermal solidification of the fiber fabric and also for optimization of its forming behavior, thermoplastic bonding fibers, such as PES fibers and PES bicomponent fibers, were used in different concentrations and with different fiber lengths.

Tool and process optimization

The Yanfeng Automotive Interiors company made a BMW door panel mold available for blow-in trials with a 3D contour. The mold had first of all to be equipped with an air-permeable blow-in top shell. This was made of glass-fiber-reinforced plastic at TITK and fitted with two programmable blow-in nozzles. The mold surface is divided into two areas in the blow-in top shell, which are separated from each other by an adjustable comb. This enables each section to be filled separately. The contour of the top shell and the position of the blow-in nozzles was adjusted over several optimization steps.

In the next step, continuous dispensing of fiber material from the fiber feeders had to be ensured. The feed chutes available in the industrial sector are designed for textile staple fibers and cannot be used for dispensing short wood fibers without making the appropriate adjustments. Not only were optimizations of the roller spacing and speeds necessary but also trials with different fiber blends of short wood fibers and long synthetic fibers. The long-fiber content on the one hand improves transportation behavior but on the other hand subsequently serves to support the forming behavior and the thermal solidification of the fiber fabric.

Once the feed chutes were adjusted, the blowing-in process with the adjustable swiveling nozzles was programmed. Various parameters can be varied:

- Air speed
- The quantity of fiber fed in with the air stream
- Duration of blowing
- Swivel range of the nozzles
- Swiveling speed.

The most suitable variant proved to be filling the 3D mold in several steps. First of all, section 1 (map pocket) of the mold was filled by nozzle 1 (Figure 5). The areas further away from the nozzle were handled with a higher air speed. To reduce air turbulence in the mold the air blowing in must be routed out again through the perforated top shell and the air-permeable rim, and the air speed matched to the fill level of the mold.
Area 2 (middle section and sill) was filled next via nozzle 2 (Figure 5). Here, too, three steps were programmed to achieve an optimal distribution of the fiber. Once the mold was completely filled, a compression stroke with the blow-in top shell was introduced to obtain a high-

er pre-compaction of the fiber fabric. The filling study in the illustration shows the gradual filling of a door panel geometry.

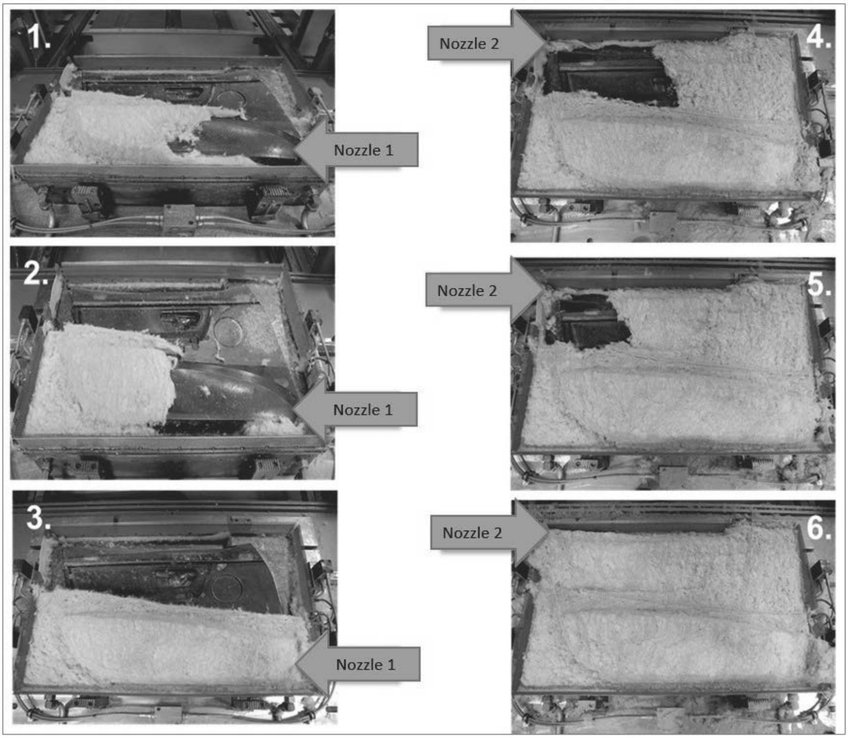


Fig. 5: Filling the sections

Once the mold is filled and the fiber material pre-compacted, the blow-in top shell is lifted and the sliding table moves into the compression station where the fiber fabric is consolidated under pressure to produce the finished component. What is important for an optimal compaction of the material in this case is a precise matching of the surface dimensions of the fiber fabric and the mold gap which is set.

The accuracy of fiber dispensing was checked in a series of filling tests and falls within a fluctuation range of around 5%. With optimum mold filling and pre-compaction of the fiber fabric, complete 3D components could thus be manufactured.

Component quality and mechanical properties

In order to determine the mechanical properties of natural-fiber components which include a proportion of sCF and are produced by the 3D fiber-blowing method, samples were taken from different areas of the door trim panel for mechanical testing (see Figure 6).

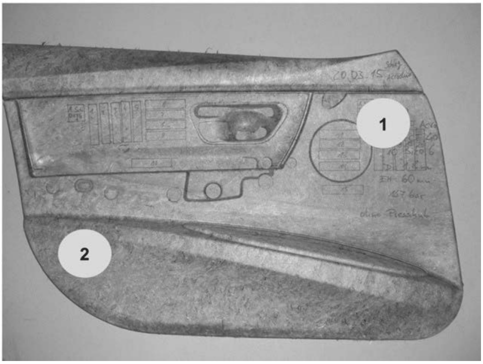
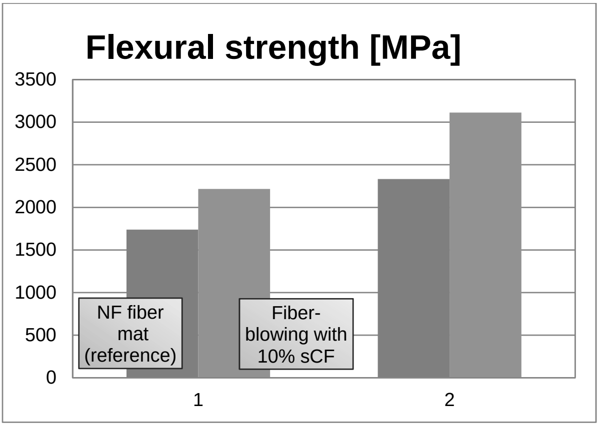


Fig. 6: Samples taken from the 3D component

The test specimens taken from different sampling points were subjected to checking of the weight per unit area, component thickness, composite density and of mechanical properties in the bending test. The properties of the composite were evaluated in comparison with components made of needled wood-fiber mats with acrylic resin binder produced by the Fibrowood process (composition of 78% wood fiber and 22% synthetic fiber). Table 1 shows the weights per unit area and the composite densities from the two sampling areas.

Table 1: Composite properties at different sampling areas

	Area	**Fiber mat (reference)** 78% wood / 22% synthetic fibers	**Fiber-blowing (Acrodur)** 80% wood / 10% PES bicomponent fiber / 10% sCF
Density [g/cm³]	1	0.867	0.852
	2	0.825	0.787
Weight per unit area [g/m²]	1	1700	1750
	2	1670	1750
Fiber content [%]	1	/	7.8
	2	/	9.6



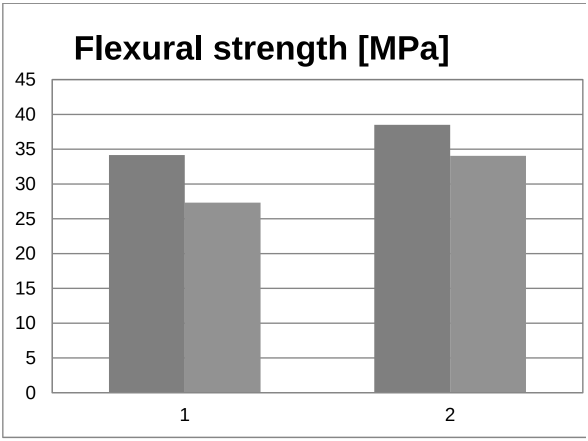
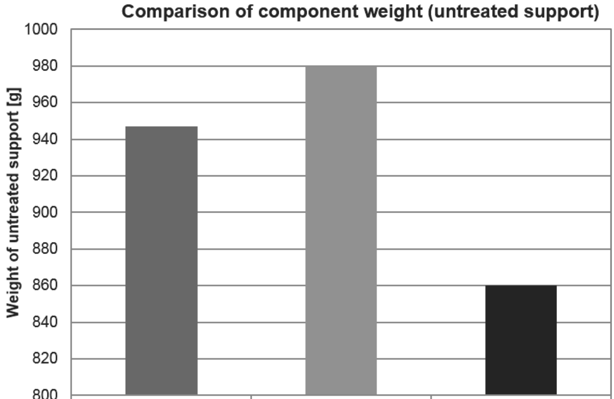


Fig. 7: Comparison of flexural properties

Figure 7 shows a comparison of test values from the 3-point bending test. It is clear that with an admixture of 10% sCF the stiffness level increases. Furthermore, there is a strong correlation of density and fiber content, as can be seen in area 2. The high tensile modulus of elasticity of the admixed carbon fibers is also expressed in the higher figures for the modulus of elasticity of the composite. What is of decisive importance for utilization of the fiber properties of the sCF is force transmission through the matrix. Sufficient adhesion of fiber and matrix is essential.

Weight reduction

In accordance with the project's objectives, the component weight could be reduced by about 10% by using sCF (see Figure 8) and mechanical properties increased with good fiber-matrix adhesion. The morphology of the different fiber materials and the resultant deposition behavior in the mold have a decisive influence here.



	Fiber mat (reference)	Wood fiber, fiber blowing	Wood fiber + 10% sCF fiber blowing
Weight of untreated support [g]	947	980	860

Fig. 8: Comparison of component weight (untreated support)

Summary and outlook

The fiber-blowing process is a new and innovative method for manufacturing fiber-reinforced moldings. This technology has been further developed at TITK and has been used for the first time to make highly compressed composite components.

The potential of the method has been demonstrated with the aid of a demonstrator component. The entire process chain can be realized using the technology available on the market and can be put into practice with manageable development effort. Due to the fact that the fibers are deposited directly with a close approximation to the final contours and the omission of cutting and blending processes together with the possibility of using recycled fibers, fiber blowing is a method which is thrifty with resources, environmentally friendly and has a high innovation potential.

Bibliography

[1] anon.:
Plant layout
Robert Bürkle GmbH 2014

[2] Galan, J.:
Internal company presentation
Yanfeng Automotive Interiors

It doesn't get greener than this!

Sustainable, economical, safe: engineering recyclates for the automotive industry

Dipl.-Ing. **A. Hoffmann**, Hoffmann + Voss GmbH, Viersen

Abstract

The drive to save fuels has paved the way for lightweight plastics in many automotive applications. If this green approach is rigorously pursued virgin material can in many cases be replaced by recompounds. This brings all kinds of benefits: recompounds are usually cheaper than virgin material, valuable resources are saved, waste is avoided, and the CO_2 footprint is improved. In addition, the German End-of-Life Vehicles Ordinance requires that more recycled material is used in order to prevent waste. As far as quality is concerned, the recompounds do not need to hide behind virgin material: extensive incoming goods inspections, processing on extruders of the latest type, and in-production laboratory tests guarantee a high-quality recompound with defined mechanical properties which is available even in large quantities over the entire lifetime of an automobile.

1. Areas of application and limits

Again and again negative attitudes are observed when recompounds made from industrial waste are used. Of course, recompounds will not advance into every area occupied by virgin compounds. We agree that recompounds should not be used in medical technology nor in the food industry. The use of recompounds in 'safety components' should also be viewed with caution.

Apart from this, recompounds offer all of the features which virgin materials also offer. Carbon fiber, glass fiber, mineral fiber are used as reinforcement materials; flame retardants, light stabilizers or heat stabilizers, hollow glass spheres and many other additives are used in our recompounds.

In addition, medium-sized companies offer the possibility of setting properties which go beyond those of virgin material, such as, for example, an ABS GF 13 or a PC-ABS HF with a high MVR *and* a high Vicat value. Even colored recompounds are possible! In recent years, light gray, white and orange formulations have come onto the market for different applications, such as electronics boxes, roof control modules and housings for power converters.

2. Latest state of the art

Recompounds can do more! In many cases a close contact between the raw material supplier, injection molders and the OEM makes it possible to employ high-quality, laboratory-tested recompounds in order to conserve resources and minimize the use of virgin materials.

No longer do buyers and developers need to have explained to them what recompounds or recyclates are. In the meantime there are many applications where they have replaced virgin materials. However, behind this 'RE' tag are often different understandings of quality. It can thus be sufficient for a processor simply to convert a regrind into pellet form. Another processor might supply his customers with defined and customized recompounds. The boundary between cheap repelletized material and high-quality recompound is a fluid one.
While an injection-molding company previously moved in favor of a recompound for reasons of cost, today more and more attention is given to 'green products'. Recompounds improve the CO_2 footprint and help, almost incidentally, to reduce the amount of waste.
Here the DY recompounds from Hoffmann + Voss do not need to lag behind virgin materials. Their properties are defined in consultation with the customer and in-production inspections are carried out. Acceptance test certificates according to DIN EN 10204 3.1 of course go without saying and in the automotive sector are a condition of delivery. We produce on the very latest systems with which high torques can be transferred and thus damage the polymer as little as possible. Our laboratory with its injection-molding machines for producing test specimens is permanently adjusted to meet customer requirements and standards. We have accordingly invested in the last two years in an MVR measuring instrument (according to ISO 1133 1/2), a Vicat/HDT device, a GWI unit, and a teraohmmeter. In addition, we have the capability in-house of measuring the FOG and VOC emissions from our recompounds in accordance with VDA 278. In this regard we are the only supplier of recompounds who can test emissions with batch accompaniment on the test certificate. Furthermore, our laboratory can also carry out impact and notched-impact testing according to IZOD and Charpy, measure tensile stress, bending stress, ash residue, fire behavior according to UL 94 V and HB, density, and color according to LAB.

3. What are the customer requirements? What information does the recyclate supplier need?

In this way our recompounds have found their way into the automobile and into air-conducting parts. Recompounds are also used in the construction and electrical industries. Different requirements apply here of course: in the construction industry great importance is often attached to good weathering resistance. Here we have, together with our customers, developed special UV- or hydrolysis-resistant recompounds.
In the electrical industry the emphasis is mainly on the fire behavior of components. Components must be 'UL-listed' and the plastic thus have very special properties with regard to its ignition or self-extinguishing behavior. Here we have developed our DYFENCE polycarbonate recompound series. We hold a 'yellow card' for the DYFENCE grades – in other words, after flame treatment according to UL 94 V0 they extinguish automatically.

An important customer requirement is quantity reliability. The percentage of production scrap is decreasing all the time and what is still available is of increasingly poor quality. Even greater efforts must be made to gain a high-quality recompound from waste material. In addition to comprehensive production inspections this also includes complex incoming goods inspections. But even the OEM can help the compounder to maintain his production on the basis of a secured wide range of material (regrind). Accordingly, color specifications for parts in the non-visible area can be defined more broadly, mechanical properties, such as notched impact, need not be upwardly limited, or a greater MVR tolerance can be accepted. As a result, it is possible to draw on more and larger sources of raw material. There is thus an increase in the quantities available. In addition to the mechanical properties of the recompound to be delivered, the most important question before submission of a tender is what quantity is expected over the term of a contract. We believe that an intensive and above all an honest exchange between supplier and OEM or TIER 1 is important in achieving a successful SOP of this kind.

But even though recompounds are products which require more consultation than virgin material, there are nevertheless many applications in which a high-quality, laboratory-tested recycled material can be used in accordance with the goals of sustainability and resource conservation.

4. About Hoffmann + Voss GmbH

HOFFMANN + VOSS GmbH is company which has been active for almost 55 years and is competent in all aspects of supplying polymer raw materials.

Over the years our compounding facilities have changed as radically as the public image of compounding and recycling and the demands of users. With growing interest in raw-material cycles and the increasing possibilities for the use of recompounds, so too have our activities and engagement increased in the production of high-quality compounds and recompounds which are colored, reinforced and formulated in accordance with the demands of the customer.

The production and utilization of recompounds means that resources are conserved.

Our polymers are used in the construction, electrical and automotive industries. Together with our customers we develop special formulations to give the plastics the properties which are wanted. In addition, we develop for our customers concepts for reusing production waste ('closing the loop').

Tinuvin® 880 – novel light stabilizer for automotive interior applications

Introduction of a new light stabilizer for PP/TPO for automotive interior applications, enabling improved secondary properties such as no blooming and no stickiness

Dipl.-Ing. **G. Huber**, BASF, Basel, Switzerland

1. Market trends

Nowadays consumers are looking for more functionality, greater comfort and overall higher quality in their automotive cockpit. OEMs have reacted to this trend through stronger differentiation and more stringent specifications in regard to plastic parts. This includes more stringent supply conditions, for example, in visual surface aesthetics (gloss, anti-scratch performance), haptics (no sweat-out, no stickiness) and emissions/organoleptics.

2. The rôle of migration in automotive polymer grades

To meet the ever-increasing standards for automotive PP/TPOs (the materials of choice in today's car), the selection of the appropriate light stabilizer package for interior applications has to provide both properties:

- Primary properties: light stability (LS) and long-term thermal stability (LTTS)
- Secondary properties: such as no stickiness, low/no emissions and low/no odor

To improve the perceived quality of automotive interiors, the loading level of anti-scratch additives (preferably cost-attractive migratory systems) has increased over the recent years. This ever higher level of migratory anti-scratch additives in combination with faster processing conditions (resulting in different polymer morphologies) and the use of high-flow polymers (high MFI grades) can lead under unfavorable circumstances to increased migration inside the polymer. Higher migration rates can potentially lead to a blooming/sweating-out of additives onto the surface of the polymer. As polymer parts in cars are very often exposed to direct or indirect sunlight, the UV radiation of the sunlight can break down these migration products and sticky compounds can be created. In this way a sticky surface layer can occur (Figure 1).

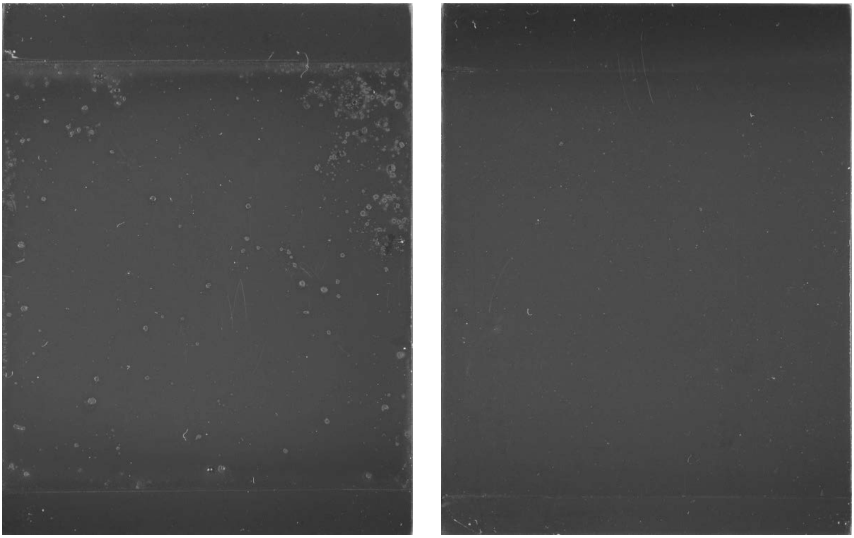


Figure 1: Plaques made of a typical automotive PP/TPO for use in interior applications. The left-hand material is stabilized with a typical ester HALS as light stabilizer, whereas the right-hand plaque uses the new Tinuvin® 880. It is can be clearly seen that after about half a year of aging the left-hand material exhibits a surface layer which is very sticky to the touch whereas the surface of the material on the right-hand side is without any surface defects and has no stickiness.

3. Novel light stabilizer to overcome the problem of sticky surfaces: Tinuvin® 880

As major additive supplier to the polymer industry, BASF started several years ago with R&D work to investigate the sticky-surface-layer effect. As result of this work a new light stabilizer has been launched: Tinuvin® 880.

Tinuvin® 880 is a unique light-stabilizer molecule, specifically designed to comply with the most demanding automotive industry requirements for PP/TPO-based parts in the interior and exterior. It delivers outstanding PP/TPO stabilization performance with regard to UV degradation, even at low concentrations, with no blooming/stickiness on TPO surface parts. As a 100% pure solution (no master batch), formulators have the ability to make unlimited formulations to meet the best cost-performance requirements.

Tinuvin® 880 provides superior light stability at much extended light exposure times and a superior thermal stability at very high temperatures, maintaining excellent mechanical properties (Figures 2, 3 and 4).

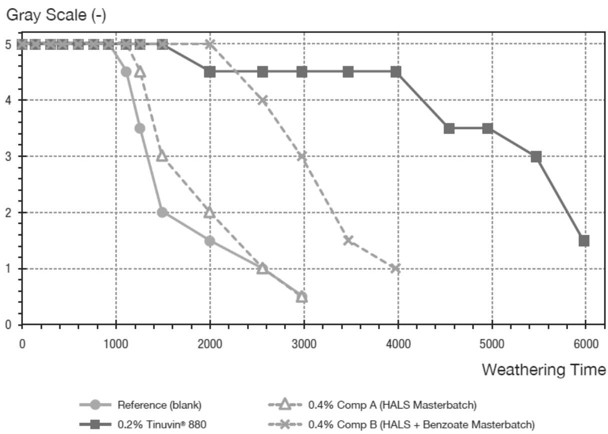


Figure 2: Performance of different formulations weathered according to VW PV 1303. The chart shows the change in visual impression expressed on the gray scale over time. The superior light stability of Tinuvin® 880 can be clearly seen (for example, at gray scale ‘4’ → approximately doubling the lifetime).

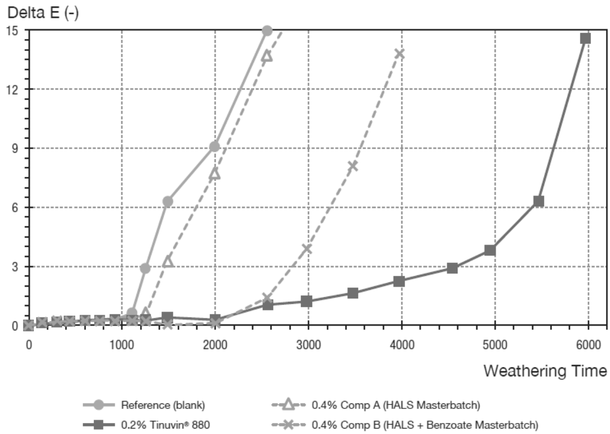


Figure 3: Performance of different formulations weathered according to VW PV 1303. The chart shows changes in Delta E over time. The superior light stability of Tinuvin® 880 can be clearly seen (for example, at Delta E '3' → approximately. doubling the lifetime).

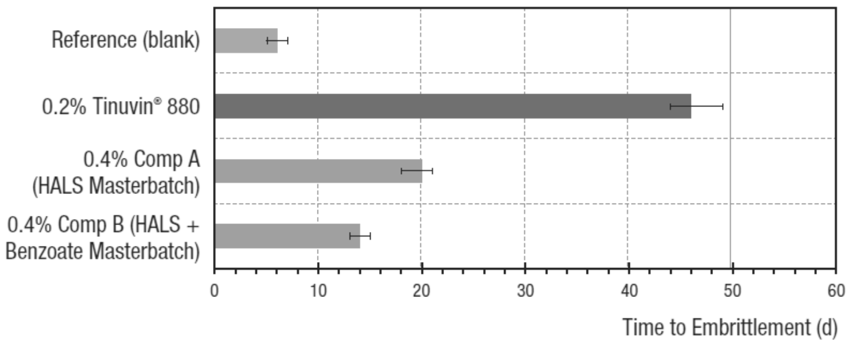


Figure 4: Performance of different formulations in regard to long-term thermal stability (LTTS) at 150 °C. Failure criterion: 'embrittlement'

The durable dust-free product form of Tinuvin® 880 provides easy storage and handling, lowers downtimes and increases productivity for compounders and masterbatchers.

Characterization of microcellular plastics for weight reduction in automotive interior parts

Dr. **J. Gómez-Monterde**, SEAT SA, Martorell, Spain;
Dipl.-Ing. **J. Hain**, Volkswagen AG, Wolfsburg;
Prof. Dr. **M. Ll. Maspoch**, Centre Català del Plàstic / Universitat Politècnica de Catalunya-BarcelonaTech, Terrassa, Barcelona, Spain

Abstract

The present work deals with foaming plastic materials in order to reduce weight, cost and carbon footprint in automotive parts. Glass-fiber-reinforced polypropylene (PP GF) was injection-molded in the solid and foamed states by means of the already known MuCell® process and a newly emerged technology, IQ Foam®, developed by Volkswagen AG. Both processes were combined with the complementary tool technology of core-back expansion molding. By increasing the thickness of the part, the apparent density decreased but the flexural stiffness was greatly enhanced. The new IQ Foam® technology is able to produce foamed parts with properties comparable to that of the MuCell® process, offering additional benefits such as cost-effectiveness, ease of use and machine-independence.

1. Introduction

Regulatory constraints and the increase in environmental awareness force the automotive industry to take different strategies to reduce greenhouse gas emissions and air pollutants. For example, electric and hybrid-drive technologies, efficiency improvements in conventional internal combustion engines, alternative fuels and lightweight construction.

It has been estimated that saving 100 kg in the bodywork cuts CO_2 emissions by 10 g CO_2/km [1], so current trends focus on replacing conventional materials with lighter ones. Nowadays, plastic materials represent around 18% of the overall vehicle weight and its use in automotive is expected only to grow [2]. For this reason, foaming injection-molding techniques emerge as a promising method of reducing weight in plastic components.

The present contribution deals with the characterization of microcellular thermoplastic foams obtained by injection molding, as a preliminary approach towards lighter, cheaper and more environmentally friendly automotive interior parts. The effect of mold cavity expansion through the core-back tool technology on foaming behavior was studied. Moreover, a comparison between MuCell® and IQ Foam® foaming injection-molding technologies is presented, in terms of morphology and the tensile, flexural and impact properties of microcellular parts produced by both processes.

2. Foaming injection-molding technologies

Of the different technologies developed for foaming through injection molding, this study focuses on the MuCell® and IQ Foam® processes, whose operating principles are as follows:

- *MuCell*®. The microcellular injection-molding MuCell® process was developed by the *Massachusetts Institute of Technology* (*MIT*) in the 1990s and since then it has been licensed and commercialized by *Trexel Inc.* (USA) [3]. The fundamentals of MuCell® technology consist basically of dissolving the blowing agent under supercritical conditions (*SCF*) in the molten polymer at the plasticizing unit, forming a single-phase solution. The pressure drops inducing cell nucleation and growth occur at the entrance of the mold, so foaming takes place inside the mold cavity.

The advantages offered by MuCell® include weight reduction, improved dimensional stability, energy and clamping-force decrease and cycle-time reduction [4]. However, there are a few limitations, such as lower surface quality and deterioration of mechanical properties. Additionally, as illustrated in Figure 1(a), using MuCell® involves new equipment and modifications in comparison with conventional injection molding. Specifically, an *SCF* metering unit, a special and longer reciprocating screw as well as back and front check valves are required. Regarding control of the process, additional variables, such as the *microcellular plasticizing pressure* (*MPP*) and the opening and closing of the gas injectors, must be regulated.

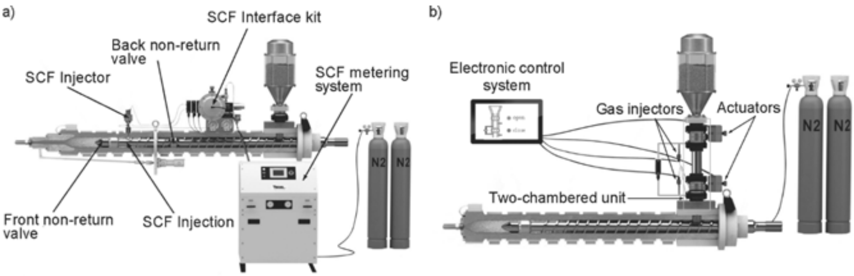


Fig. 1: Plant concept for (a) MuCell®; (b) IQ Foam® foaming technologies. Modified from [5].

- *IQ Foam*®. IQ Foam® has been developed recently and is expected to be integrated into industrial production in forthcoming years. It was conceived by *Volkswagen AG* (Germany) with the aim of reducing complexity and cost as compared with other available processes. The main equipment consists of a two-chambered unit installed between the hopper and the feed of any conventional injection-molding machine (Figure 1(b)), where polymer is impregnated with gas before melting. This unit was patented in 2014 [6] and contains two gas injectors to introduce the physical blowing agent, valves to regulate the flow of gas and two actuators to allow polymer pellets to pass through the unit and to lock each chamber. IQ Foam® incorporates the gas in the feed area of the plasticizing unit together with the polymer in pellet form. It is worth pointing out that gas is supplied under moderately low pressure [7] directly from the gas cylinder, without the need for gas-metering equipment. The only important modification of the injection machine is sealing the back of the screw to prevent gas escaping.

On the other hand, the foaming process can be controlled only by the gas pressure. It can, accordingly, be easily automated and driven by an electronic system managing the actuators and gas injectors regardless of the original software control of the injection-molding machine.

Consequently, IQ Foam® emerges as a potentially cost-effective and machine-independent process, easy to start up and reducing both the weight and cost of plastic products significantly.

- *Core back*. Core-back expansion molding is a complementary tool technology able to improve surface quality, but also increase density reduction, the stiffness-to-weight ratio and save weight in foamed thermoplastic parts. Firstly, the cavity is volumetrically filled close to solid weight by a polymer/gas mixture. The cavity is filled at high injection speed so as to prevent pressure drop and foaming. After a delay time within which a solid skin forms, the cavity is expanded and the increase in volume induces a sudden pressure drop, promoting foam generation inside the part [8]. As thickness increases, lower densities are reached. The entire cavity can be expanded, or only partially in defined areas of interest.

3. Materials and methods

- *Material*. A 20% chemically-coupled high-performance glass-fiber-reinforced polypropylene compound (PP 20GF *Fibremod™ GE277AI*) supplied by *Borealis AG* (Germany) was used. It has been specially developed for demanding applications in the automotive industry, with a density of 1.04 g/cm^3 (ISO 1183) and a melt flow index of 12 g/10 min (ISO 1133).

- *Injection molding*. The PP 20GF compound was pre-dried at 80 ºC for a minimum of 3 hours, as recommended by the supplier. Rectangular plates of 400 x 130 mm^2 (Figure 2) and variable thickness were injection-molded with the MuCell® and IQ Foam® processes, combined with the core-back technology. Firstly, solid and foamed plates 3 mmthick were obtained, reducing the weight by 10% as compared with the unfoamed part. Then, two series of foamed samples combined with the core-back technology were injection-molded, with an enlargement of the cavity from a basic wall thickness of 3 mm up to 3.3 mm and 3.7 mm.

The solid and MuCell® foamed plates were produced in an *Arburg 570C Allrounder 2000-675* injection machine with a clamping force of 2000 kN (*Arburg GmbH*, Germany), whereas the IQ Foam® foamed plates were injection-molded using a *KraussMaffei 200-1000/390/CZ Multinject* injection-molding machine (*KraussMaffei Group GmbH*, Germany) with 2000 kN of clamping force and equipped with the IQ Foam® foaming devices. The same injection-molding parameters were employed to produce the samples: a melt temperature profile of 40-210-230-240 ºC from hopper to nozzle, an injection speed of 100 cm^3/s, a mold temperature of 30 ºC and a cooling time of 45 s. The shot volume for solid plates was 190 cm^3, with a holding pressure of 300 bar applied for 10 s, whereas foamed samples were injected with 165 cm^3 of shot volume, and using nitrogen as blowing agent. A 0.5% content of gas was introduced at 34 bar of pressure during MuCell® processing. As the IQ Foam® equipment is only controlled by the gas pressure, which was 25 bar, the rest of foaming parameters were not measured.

- *Morphology and apparent density*. After the injection procedure, the apparent density of the plates was calculated by weighing and measuring their volume The morphology of the foamed specimens was analyzed with cross-sections 10 mm wide taken midway from the injection gate both in a parallel (MD) and in a transversal direction (TD) (Figure 2(a)).

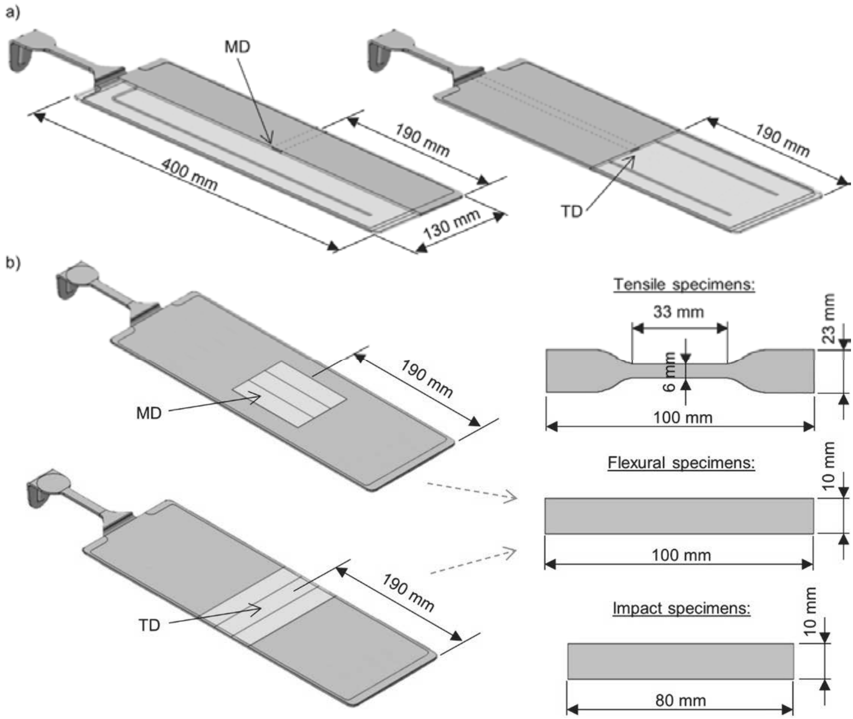


Fig. 2: Schematic representation of injection-molded plates and samples extracted for (a) morphological analysis; (b) mechanical testing.

Fracture surfaces resulting from cryogenic fracture were examined by scanning electron microscopy (SEM) using a *JEOL JSM-560* microscope (*Jeol Ltd.*, Japan). Micrographs were adjusted for an appropriate level of contrast and morphological parameters, such as cell size, cell density and skin thickness, were determined with the aid of Igor Pro® (*Wavemetrics Inc.*, USA) and Matlab® (*The MathWorks Inc.*, USA) software.

The glass-fiber-reinforcement content was obtained by determining the ash by the direct calcination method, following the guidelines set by the ISO 3451-1 standard.

- *Mechanical properties*. The specimens for mechanical tests were machined out of the rectangular plates according to the schemes shown in Figure 2(b). At least five samples of solid and foamed materials were tested at room temperature.

Tensile tests were carried out on a universal testing machine – *Zwick/Roell Z010* (*Zwick GmbH & Co. KG*, Germany) – using a 10 kN load cell, at a crosshead speed of 50 mm/min and an initial distance between clamps of 72 mm, as indicated in the ISO 527 standard.

Flexural tests were conducted following the ISO 178 standard, on a *Galdabini Sun 2500* (*Galdabini SPA*, Italy) testing machine equipped with a 5 kN load cell, at a crosshead speed of 10 mm/min and a span length of 80 mm.

Charpy impact tests were made on unnotched samples in a flatwise configuration, using an instrumented *Ceast Resil* impactor (*Instron Ltd.*, UK) equipped with a 15J hammer. The pendulum had a length of 0.374 m and a reduced mass of 3.654 kg. It was impacted at an angle of 99º, resulting in an impact rate of 2.91 m/s. The span length was 62 mm, and tests were performed according to the recommendations given by the ISO 179-2 standard.

4. Results and discussion

- *Morphology and apparent density*. SEM micrographs taken from MuCell® and IQ Foam® microcellular samples are plotted in Figure 3. All samples exhibited a material structure consisting of a solid external layer and a foamed core, which is inherent in the injection-molding process. It has been reported that foaming PP is very difficult because of its low melt strength and crystalline regions [9]. However, SEM images exhibit a uniform cell structure. It is therefore clear that the governing mechanism for cell nucleation was heterogeneous nucleation induced by glass fiber. According to the cClassical nucleation theory [10], undissolved gas trapped at the filled/polymer interface promotes the creation of a multitude of sites for cell formation requiring much lower activation energy for bubble nucleation, accelerating cell nucleation and the development of a large number of cells with a small cell size. Moreover, the added fillers increase the melt strength of the material [11], contributing to prevent cell coalescence and improving its foaming behavior.

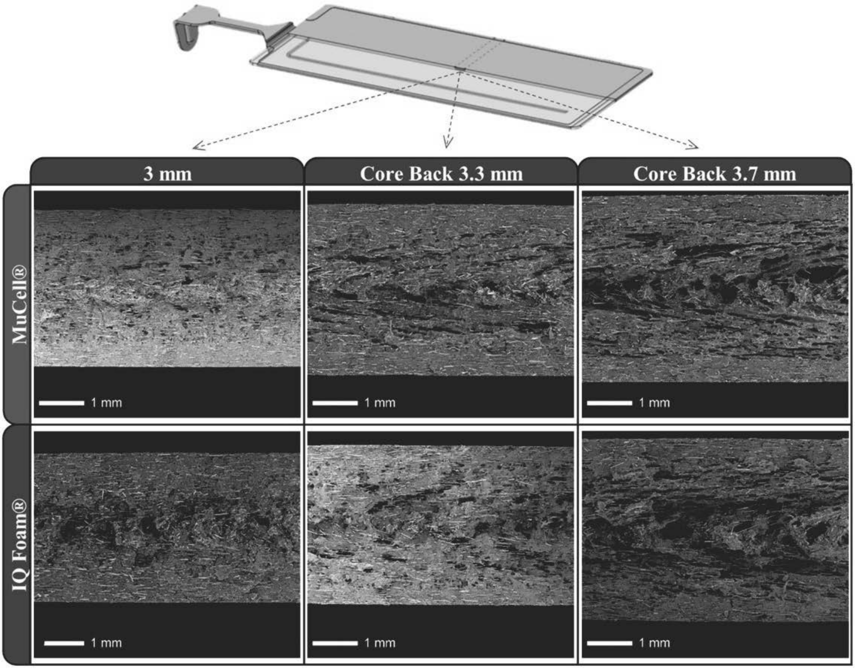


Fig. 3: SEM micrographs of MuCell® and IQ Foam® foamed plates taken in the MD direction.

The morphological parameters and apparent density results are shown in Table 1. The apparent density of the solid plates ranged around 1.04 ± 0.01 g/cm^3. By foaming, it was decreased by 10% without the use of core-back technology. As the final thickness and overall volume increased by mold opening, the apparent density decreased by up to 14% and 21% for the final thickness of 3.3 mm and 3.7 mm respectively.

Mostly spherical cells can be observed at the starting thickness of 3 mm without enlargement of the cavity thickness. In the core-back method, the cavity was volumetrically filled with the polymer/gas system, after which the thickness of the mold cavity was quickly increased up to 3.3 mm and 3.7 mm thereby reducing the pressure and thus enhancing cell nucleation [8]. Stretching forces caused by the mold opening could bring about cell elongation and distortion, also accompanied by shrinkage of cell walls during polymer cooling, resulting in higher diameters [12]. As the thickness increased, the core region remained at the molten state for a longer time, leading to thinner solid skin layers.

Table 1: Morphological parameters of MuCell® and IQ Foam® foamed PP 20GF plates.

Condition	Section	Density (g/cm³)	Skin thickness (mm)	Cell density (cells/cm³)	Cell size (µm)
MuCell® 3 mm	MD	0.94 ± 0.01	0.41	$7.1 \cdot 10^5$	9 - 165
	TD	0.94 ± 0.01	0.42	$8.5 \cdot 10^5$	9 - 125
MuCell® / core back 3.3 mm	MD	0.90 ± 0.01	0.46	$8.4 \cdot 10^5$	9 - 263
	TD	0.90 ± 0.01	0.38	$8.2 \cdot 10^5$	9 - 223
MuCell® / core back 3.7 mm	MD	0.82 ± 0.01	0.41	$6.1 \cdot 10^5$	4 - 286
	TD	0.82 ± 0.01	0.31	$6.8 \cdot 10^5$	3 - 280
IQ Foam® 3 mm	MD	0.94 ± 0.01	0.70	$4.4 \cdot 10^5$	6 - 195
	TD	0.94 ± 0.01	0.67	$4.3 \cdot 10^5$	9 - 128
IQ Foam® / core back 3.3 mm	MD	0.90 ± 0.01	0.41	$4.5 \cdot 10^5$	4 - 234
	TD	0.90 ± 0.01	0.42	$5.8 \cdot 10^5$	7 - 222
IQ Foam® / core back 3.7 mm	MD	0.82 ± 0.01	0.40	$5.5 \cdot 10^5$	3 - 276
	TD	0.82 ± 0.01	0.32	$6.8 \cdot 10^5$	3 - 288

Regarding the comparison between parts produced by MuCell® and IQ Foam®, well-defined and uniform cell structures can be observed in the micrographs in Figure 3, which indicate that microcellular reinforced thermoplastics can be successfully developed by either foaming technology. Slightly thicker solid skins of IQ Foam® without core-back expansion were determined from Table 1. Despite the cell density measured in all samples being in the order of 10^5 cells/cm³, those samples obtained by the IQ Foam® process were slightly lower. Since the same injection-molding parameters were employed for processing with both methods, differences in the amount of blowing agent used for each foaming process emerges as the main reason for these morphological differences. In contrast to the MuCell® technology, the gas in the IQ Foam® process was incorporated into the polymer in pellet form. The key parameter controlling the process was the gas pressure, so the gas content injected into the polymer was not measured and cannot be directly compared. Nevertheless, a smaller amount of blowing agent in the IQ Foam® molded parts is expected due to the low solubility of the gas in the solid pellets, which would explain the increased solid layer determined in the 3 mm-thick specimens, as well as the decrease in cell density. However, no differences in cell size between the two processing technologies were reported.

Of particular interest could be the analysis of fiber length from the comparison of the two foaming technologies. As described above, MuCell® equipment requires a special design of the screw for optimizing the polymer/gas mixture. Increased shear stresses in this zone could result in higher fiber breakage. On the other hand, the blowing agent in the IQ Foam® process is introduced in the feed region of a conventional injection machine, which means that fibers are no longer subject to additional shearing forces. Nevertheless, measurements of fiber length provided values falling within the range of 748 ± 174 µm for all solid, MuCell®- and IQ Foam®-derived samples, which suggests that the special machinery designed for MuCell® did not affect fiber length in case of short-fiber-reinforced thermoplastics. Fiber content remained in all specimens within the range of 20.1 ± 0.2 %.

- *Mechanical properties*. The elastic moduliobtained in tensile tests are plotted in Figure 4. All specimens experienced brittle fracture before reaching the yielding point and without necking. This behavior is due to the presence of the glass fiber. On one hand, fibers restrict matrix movement and deformation [13] and, on the other hand, stress concentrates at the fiber ends and the matrix cannot support the increased local load [14]. Figure 5 shows the flexural modulus resulting from bending tests of solid and foamed samples.

In Figures 4 and 5, it is clear that foamed samples have a lower tensile and flexural modulus than their solid counterparts.This is because cells in the core effectively led to a decrease in density and in the effective cross-sectional area. With increasing density reduction by core-back expansion, the reduction of both the tensile and flexural modulus was nearly linear, as indicated by the closeness of specific values to those of solid specimens.

Fiber-filled composites are characterized by an observed anisotropy in their mechanical properties. In all unfoamed and foamed samples from the MuCell® and IQ Foam® processes, the mean values of the tensile modulus obtained in the MD direction were about 30% higher than in the TD direction, which suggests a preferential orientation of fibers in the filling direction. In the case of flexural properties, these differences between the two directions were about 45%, highlighting the more effective reinforcing effect of glass fiber under bending loads. However, no effect of foaming nor of core-back expansion in anisotropic behavior can be determined as compared with the conventional injection-molded solid plates.

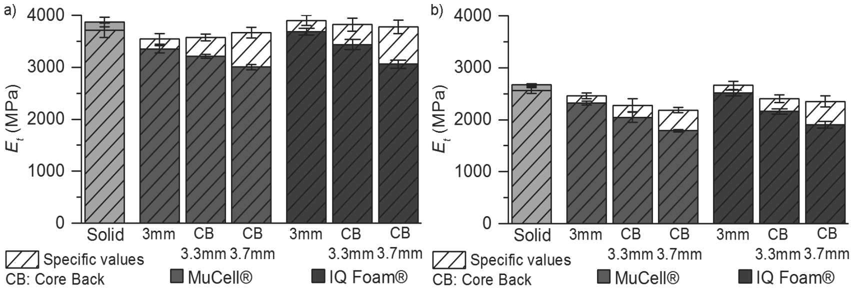


Fig. 4: Tensile modulus of solid and foamed samples obtained in the (a) MD; (b) TD directions.

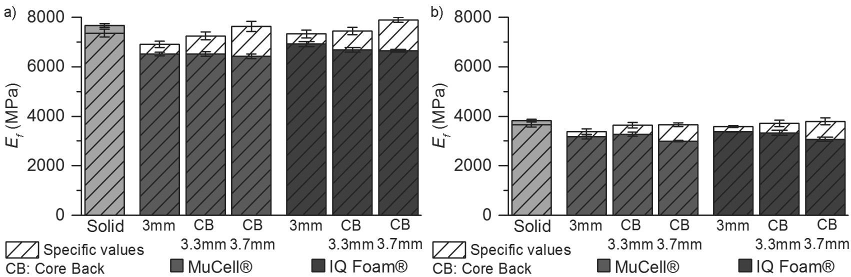


Fig. 5: Flexural modulus of solid and foamed samples obtained in the (a) MD; (b) TD directions.

As regards a comparison of the foaming technologies, the tensile and flexural moduli of samples obtained by the IQ Foam® process were higher and differed from the corresponding ones of the MuCell® process by approximately 10%. The thicker solid skins seem to be the most likely reason for this result. On the basis of the reduced amount of blowing agent incorporated in the IQ Foam® plates, the consequent reduction in cell density resulted in wider cell struts and a higher effective bearing area to withstand higher mechanical loads. These differences between foamed samples from the two processes were less marked when the core-back technology was applied and the volume cavity increased – this suggests that, as the part gets thicker, tensile and flexural properties became more dependent on apparent density and overall thickness than upon skin thickness and cell density.

Most of the literature dealing with the core-back expansion-molding process focuses on the flexural properties of the resulting foams [15]. This is due to the fact that, for engineering purposes, design criteria are based on the flexural stiffness rather than on the flexural modulus. This parameter involves the geometry of the part via the moment of inertia. For flat panel geometries, the flexural stiffness (S_f) is calculated as follows:

$$S_f = E_f I = E_f \frac{bh^3}{12} \qquad (1)$$

Where I is the moment of inertia, E_f is the flexural modulus and b and h the part width and thickness respectively. Thus, flexural stiffness is significantly increased by the third power of the thickness. Figure 6 illustrates the evolution of the relative, specific flexural strength by foaming and increasing thickness by the core-back technology. It should be noted that despite the drop in the flexural modulus, stiffness was improved by up to 200% as compared with that of the solid counterpart by increasing the thickness to 3.7 mm.

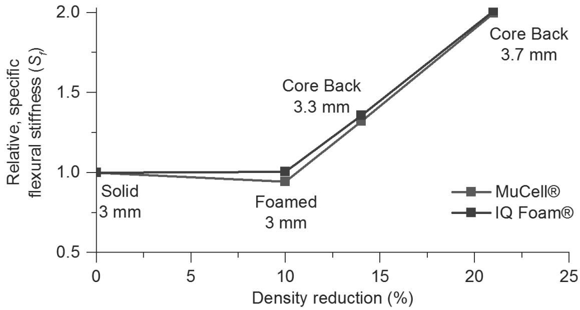


Fig. 6: Relative, specific flexural stiffness evolution with density and thickness.

The impact resistance calculated by the integral of the curves is shown in Figure 7. From these data it can be seen that impact resistance decreased by around 15% when foaming without core expansion, and by 22% and 35% while increasing the thickness to 3.3 mm and 3.7 mm respectively. In other words, foamed material is more sensitive to impact loads than to tension and bending. Since the testing method consists of an impact bending load, thickness of the solid skins played a crucial rôle in the performance of the part. By controlling a proper solid-skin thickness and fiber orientation, it would be possible to produce lightweight products without largely sacrificing the impact properties.

In addition, differences in the MD and TD values of solid samples were around 28%, but they were significantly reduced by foaming and expansion molding, reaching a difference between both directions of 5% when the thickness is raised to 3.7 mm. The impact resistance is also a property where smaller differences between the two foaming technologies were found. Due to the higher skin thickness, the impact resistance of the samples obtained by the IQ Foam®

process was around 7% higher than that of the MuCell®-foamed specimens. These differences decreased by increasing the thickness with the core-back process.

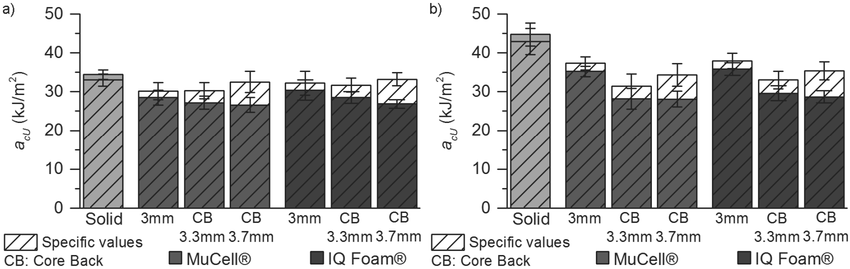


Fig. 7: Impact resistance of solid and foamed samples obtained in the (a) MD; (b) TD directions.

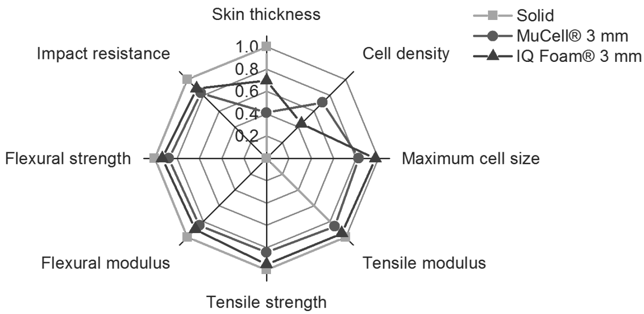


Fig. 8: Multivariable plot comparing the morphological characteristics and mechanical properties of MuCell®- and IQ Foam®-foamed samples.

5. Conclusions

In this paper the morphology and mechanical properties of PP 20GF foams obtained with different injection-molding techniques and combined with complementary tool technologies were analyzed. By pulling the core and increasing the final thickness of the part with the core-back tool process, apparent density decreased, solid skins became thinner but cells became bigger and distorted. Absolute mechanical properties decreased with apparent density but specific ones remained close to that of the solid material. Furthermore, design criterion parameters such as bending stiffness were greatly enhanced due to the build-up in overall thickness.

On the other hand, a new foaming technology, called IQ Foam® and developed by Volkswagen AG, was examined in this paper and compared with the already well-known MuCell® process. By using a minimum amount of blowing agent, foamed plastic parts obtained by the IQ Foam® process exhibited thicker solid skins and lower cell densities but in consequencehigher mechanical properties (Figure 8). Additional benefits such as cost-effectiveness, ease of operation and machine-independence enable the IQ Foam® process to produce lightweight parts with properties comparable to those of the MuCell® technology. Further research on foaming mechanisms and their effect on polymer properties will be essential in order to fully incorporate microcellular plastics into automotive parts.

6. Acknowledgements

The authors are grateful to the *Research Lab* of *Covestro AG* (Leverkusen, Germany) and the *Institut für Recycling* of the *Ostfalia Hochschule* (Wolfsburg, Germany) for their cooperation with injection-molding experiments in their facilities.

7. References

[1] Automotive. *The world moves with plastics*, company publication, Plastics Europe, Brussels 2013.

[2] Plastics. *The future for automakers and chemical companies*, company publication, A.T. Kearny Inc, Chicago 2012.

[3] EU-P 0952908.

[4] Xu, J.: *Microcellular Injection Molding*. Hoboken: John Wiley & Sons 2010.

[5] http://www.plasticportal.eu/en/thermoplastic-foam-injection-molding/c/2416.

[6] DE-P 102014212048.

[7] Hain. J.: *Thermoplastschaum-Spritzguss - neue Möglichkeiten durch IQ-Foam*. Kunstofftrends im Automobil 2015.

[8] Heim, H.P. and Tromm, M.: *General aspects of foam injection molding using local precision mold opening technology*. Polymer 56 (2015) 8 pp. 111-118.

[9] Bledzki, A.K., Faruk, O., Kirschling, H., Kühn, J. and Jaszkiewicz, A.: *Microcellular polymer and composites. Part II. Properties of different types of microcellular materials.* Polimery-W 52 (2007) 10 pp. 3-12.

[10] Colton, J.S. and Suh, N.P.: *The nucleation of microcellular thermoplastic foam with additives: Part I: Theoretical considerations*. Polymer Engineering and Science 27 (1987) 8 pp. 485-492.

[11] Mueller, J., Spoerrer, J. A. and Altstaedt, V.: *Foam injection moulding of a TPO/TPC-blend and the effect of different nucleating agents on the resulting foam structure*. AIP Conference Proceedings 1593 (2014) 7 pp. 367-373.

[12] Heim, H.P. and Tromm, M.: I*njection molded components with functionally graded foam structures – Procedure and essential results*. Journal of Cellular Plastics 52 (2016) 21 pp. 299-319.

[13] Kumar, K.S., Bhatnagar, N. and Ghosh, A.K.: *Development of long glass fiber reinforced polypropylene composites: mechanical and morphological characteristics*. Journal of Reinforced Plastics and Composites 26 (2007) 11 pp. 239-249.

[14] Thomason, J.L., Vlug, M.A., Schipper, G. and Krikor, H.G.L.T.: *Influence of fibre length and concentration on the properties of glass fibre-reinforced polypropylene: Part 3. Strength and strain at failure*. Composites Part A-Applied Science and Manufacturing 27 (1996) 10 pp. 1075-1084.

[15] Spörrer, A.N.J. and Altstädt, V.: *Controlling morphology of injection molded structural foams by mold design and processing parameters*. Journal of Cellular Plastics 43 (2007) 18 pp. 313-330.

A demonstrator for the experimental assessment of the through-process modeling of injection-molded parts made of short-fiber-reinforced polymers

An example illustrating the greater reliability of results from structural calculations using an advanced design approach and correct anisotropic characterization of the materials

E. Spini, RadiciGroup Performance Plastics,
Chignolo d'Isola (Bergamo), Italy;
A. Bernasconi, Politecnico di Milano, Milan, Italy

Abstract

Through-process modeling of injection-molded parts is nowadays the industry standard approach to the structural analysis of parts made of short-fiber-reinforced polymers. The designer has to face challenging tasks, in order to conduct accurate and reliable analyses. Complex geometries, weld lines and multiple flows make it difficult to transfer the results of tests conducted on simple specimens to the assessment of the real parts. We have designed a mold for manufacturing a demonstrator, that is, a part of sufficiently complex shape, typical of injection-molded structural parts, permitting the creation of different conditions in terms of fiber orientation, presence of weld lines and multiple injection points. The part is designed to be tested under three- or four-point bending conditions. By simulating the test conditions, the designer can compare experimental results with numerical solutions, in order to better understand the potential of the software packages he is using.

Introduction

The transportation sector is the driving force behind innovation leading to the design and development of new polymers with increasingly higher levels of performance. The need to reduce component weight requires materials which are capable of performing the same functions that only metals have been capable of achieving hitherto. In this field, polymers, and more specifically polyamide polymers, have played a very important role, especially for components operating at high temperatures and subjected to high stress. Novel nylon solutions have been introduced in keeping with the evolution towards smaller, more powerful and longer-lasting engines.

In the field of metal replacement (aluminum alloys, in particular), there are currently numerous mature applications where the replacement rate has reached 80% to 90%. Among these parts are radiator tanks, air intake manifolds, valve covers, fans and air conveyors.

However, there are other components that are still mostly made of metal, but are potential targets for metal substitution: engine mounts, hot side turbo air ducts, engine and transmission oil pans.

There are yet more applications which are being studied and for which hybrid solutions have been proposed: plastics with appropriately positioned metal inserts, or continuous-fiber-reinforced plastics. Examples of the latter are: brake pedals, suspension parts, front-end parts, car seat parts and dashboard supports.

In this context of change, producers of plastic materials for engineering uses have been investing sizable resources in the production of increasingly more reliable materials with better performance.

Another aspect, comparable in importance to the availability of suitable materials, is the access to data and more reliable design methodologies for more accurately defining the dimensions of plastic components. The traditional design criteria adopted for plastics, such as glass- or carbon-fiber-filled polymers considered as isotropic materials, are ones inherited from the metal world. Such an approach is likely to introduce severe design errors. In some cases parts may be oversized leading to unnecessary cost increases. In the opposite case, when part sizes are underestimated, additional costs will be incurred due to the need to redesign the components with a greater safety allowance.

As a result, it is necessary to change the approach to the design of engineering plastic components in order to increase the reliability of structural calculations. Such a change represents a very important step, particularly for components expected to operate in increasingly severe environmental conditions and/or plastic parts performing functions that could affect safety.

Plastics developed for metal replacement are generally glass- or fiber-filled polymers to be processed by injection-molding techniques. These materials, are, for all intents and purposes, anisotropic [1]. Fiber orientation and distribution determine the local characteristics at each point of the molded object and are dependent on the molding process.

This paper presents the results of a collaborative project by RadiciGroup Performance Plastics and the Politecnico di Milano university, in which a comparison is made between real and computed data for a plastic ‘demonstrator’.

Computations were performed using a method known as Through-Process Modeling (TPM), which the local properties of the material at each point in a finite element model to be linked with the results of the injection process simulation. More specifically, the effect of the fiber orientation is taken into account through the use of appropriate software packages for the interface and the computation of properties as a function of the fiber orientation distribution. Examples of the application of the TPM method to fatigue strength assessment can be found in [2 - 4].

Material characterization and advanced calculation approach

The material under consideration belongs to a PA66-GF50 speciality family featuring enhanced mechanical characteristics in comparison with standard products. In particular, the base formulation was modified to enhance the tensile strength and deformation at break, especially when weld lines were present. The weld lines are often the weakest place in the molded part. These improved characteristics are summarized in the graphs in Fig. 1.

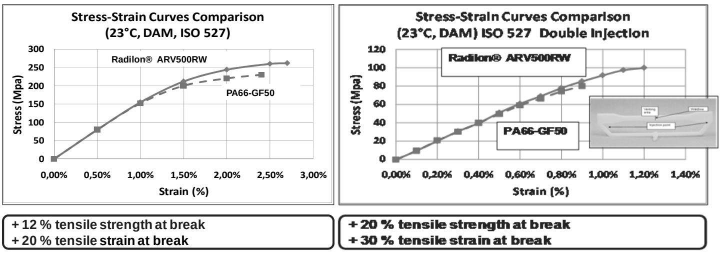


Fig. 1: Stress-strain curves of Radilon ARV500RW

In order to perform the advanced structural calculations, measurements of the characteristics of the base polymer material and the short-glass-fiber reinforcement were performed, as well as the characteristics of the samples cut out of rectangular plates at different angles with respect to the direction of melt flow. Special care was paid to the quality of the cut and the sample position, which could have a great effect on the results of measurements, based on the numerous tests performed. Material characterization was done taking into consideration the stress-strain curves at four cutting angles: 0°, 30°, 45° and 90°. Fig. 2 shows a chart of the approach used, consisting of the following sequence of steps:

Step 1: Simulation of the molding process (using appropriate software packages), which provides, among other things, the glass-fiber orientation tensor at each point and the position of the weld lines.
Step 2: Generation of a micro-mechanical model of the material with calibration of the model using the experimental results obtained for samples cut from plates at different angles.
Step 3: Mapping of the local properties of the material, using appropriate software packages, taking into account the morphology induced by the simulated molding process. Mapping is performed for each point of the mesh that will be used later on for the non-linear structural calculations.

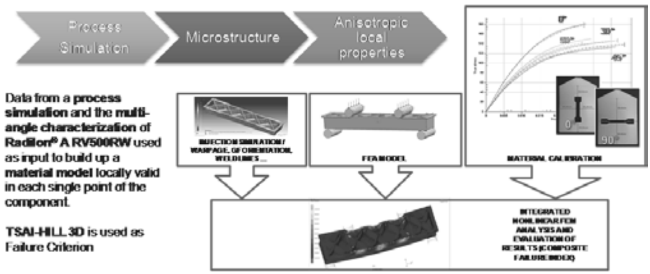


Fig. 2: Flow chart illustrating the material characterization for TPM

Description of the component

The component studied in this work is a beam having an open C section and a pattern of internal reinforcing ribs. The part is shown in Figure 3.

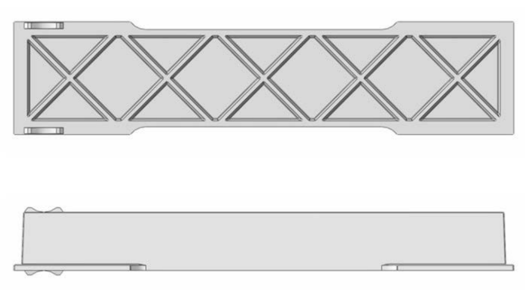


Fig. 3: Shape of the component

The component is manufactured by injection molding and the mold is designed to use different and multiple injection gates, as shown in Figure 4.

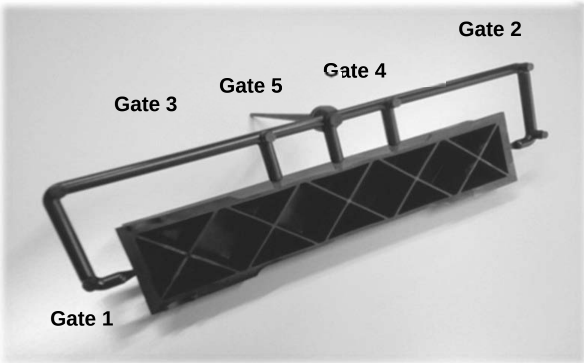


Fig. 4: Configuration of the different possible injection channels and position of the gates

Experimental tests

The part was designed to be subjected to bending tests. A four-point bending configuration was chosen for the first tests presented here. The set-up is shown in Figure 5. It comprises a four-point bending fixture and a deflectometer, which accurately measures the deflection of the part at the center point (readings of the crosshead displacement transducer would be affected by the compliance of the rig). The fixture is mounted on a MTS RF150 testing machine, equipped with a 150 kN load cell.

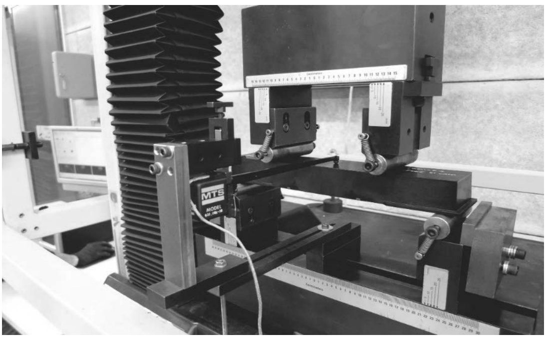


Fig. 5: Four-point bending set-up

The test was conducted in displacement control mode at a speed of 5 mm/min up to failure. Failure load and mode were different for different injection configurations.

In this paper, the results of four configurations are presented:

a) Longitudinal injection (Gate 2)
b) Double longitudinal injection (Gates 1 and 2 simultaneously)
c) Side injection (Gate 5)
d) Double side injection (Gates 3 and 4 simultaneously)

Results of the experimental tests

Three specimens for each injection configuration were tested. The results are presented in Figure 6 as superimposed load-displacement curves of one specimen for each configuration. It appears that, due to the different fiber orientation patterns, the stiffness is modified as the injection configuration changes and, additionally, the strength is affected, also because of the presence of weld lines.

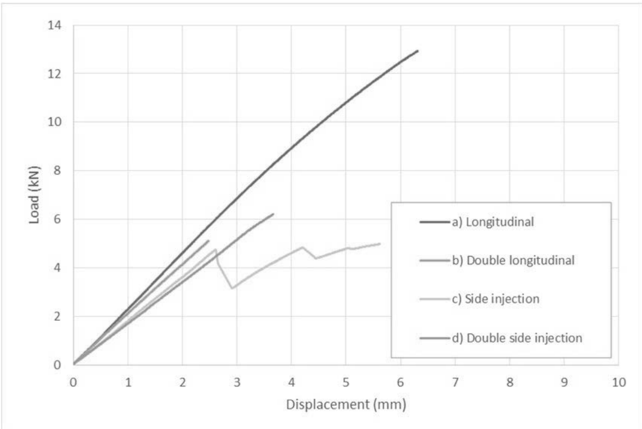


Fig. 6: Force-displacement curves

FE models

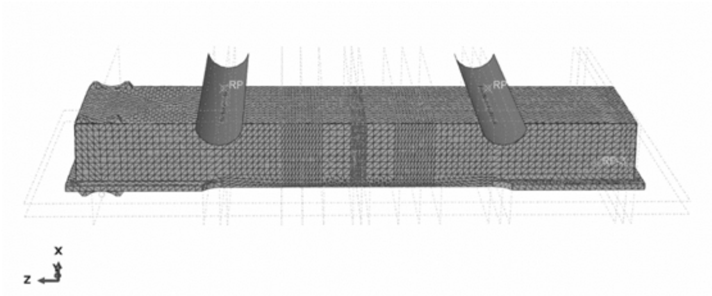


Fig. 7: Structural finite element model

The tests were simulated using Simulia Abaqus 6.14.3 Finite Element (FE) software. The FE model is shown in Figure 7. The elements are quadratic tetrahedra and the mesh size was varied in order to capture local stress fields accurately in the highly stressed regions, i.e., at the intersection of the inner ribs and the outer walls, as shown in Figure 8. Material properties were defined on the basis of process simulation analyses conducted using Moldex 3D software. Local material properties were evaluated using Digimat software, after mapping fiber orientation results from the process simulation mesh onto the structural mesh using the Digimat MAP package. The material properties were defined by the material characterization presented in the previous section and are available in the Digimat MX database. The material model is a non-linear model with plasticity, and the failure condition is defined by a strain-based Tsai-Hill criterion. A variable FI (Failure Index) is evaluated at each node. A value of FI equal to or greater than 1 indicates local failure.

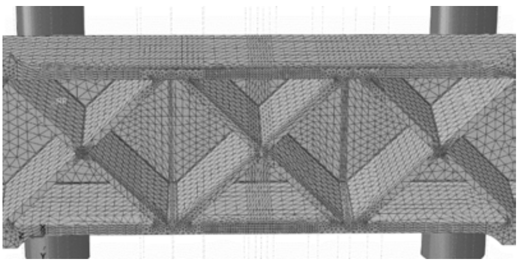


Fig. 8: Detail of the mesh refinement in the highly stressed regions

Incremental displacement of up to 8 mm with a maximum time increment of 0.05 was imposed on the rollers. The rollers were modelled as rigid surfaces, which were constrained to the model of the part through a contact interface. The presence of the lower rollers was simulated by constraining the vertical displacement of a reference point linked through a kinematic coupling to a surface corresponding approximately to the expected contact surface.

Results of the FE analyses

Four different models were built corresponding to the four fiber orientation patterns, as obtained with the four different injection configurations. The results are presented in terms of load-displacement curves, where load is defined as the sum of the reaction forces of the upper rollers, and the displacement was recorded at the node corresponding to the contact point between the part and the arm of the deflectometer.

Loads and displacements are displayed up to the time of failure, defined as the time increment during which a value of the Failure Index of 1 is found at the highly stressed location. A typical map of the failure index is shown in Figure 9.

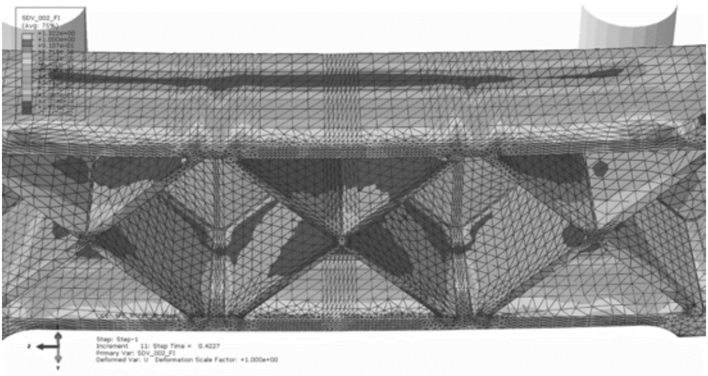


Fig. 9: Failure Index map

Load-displacement curves obtained with the four models are reported in Figure 10. The corresponding experimental load-displacement curves are superimposed on the results of the numerical simulation.

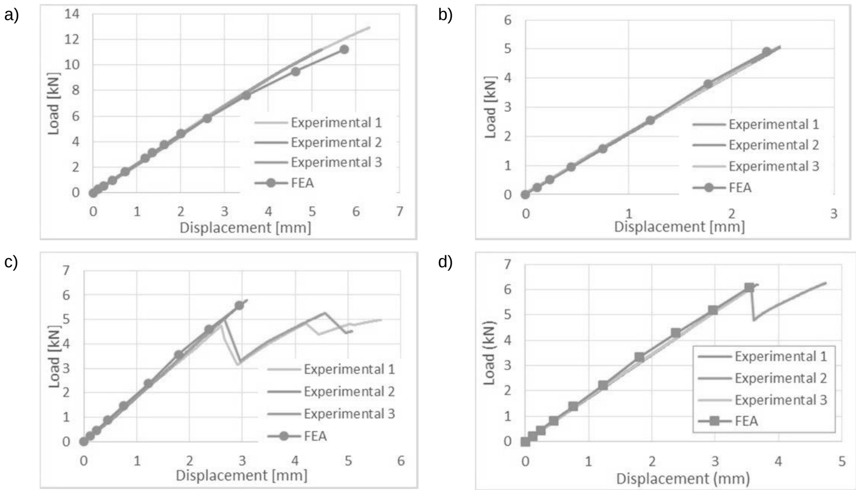


Fig. 10: Comparison of the simulated and the experimental load-displacement curves for all four cases: a) Longitudinal injection; b) Double longitudinal injection; c) Side injection; d) Double side injection

It appears that the FE models enable correct capture of the stiffness and the strength of the parts for all four injection configurations. It is interesting to compare the results obtained for the longitudinal configuration by TPM and the results that can be obtained by conducting FE analysis assuming an isotropic material with plasticity, as defined by tensile tests on standard ISO 527-2 specimens. This approach is often adopted for preliminary analysis. In this case, it is often customary to reduce the properties (elastic modulus and the plastic strain-yield stress curve) by a certain empirical reduction factor (by ⅓, for example), as dictated by the experience of the designer, in order to introduce the effect of possible misalignment of the reinforcing fibers with respect to the principal stresses.

The load-displacement curves obtained by modeling the material as isotropic, with and without empirical reduction, are shown in Figure 11, where the experimental curve and the numerical one obtained by TPM are superimposed as well. The agreement of the TPM results with the experimental results is much better than that of the isotropic models in terms of both stiffness and strength. The isotropic model correctly captures the maximum load but overestimates the stiffness, while the isotropic model with empirical reduction fails to estimate accurately both the stiffness and the strength. By assuming an orthotropic material whose properties are related to the fiber orientation distribution in the part, the stiffness and the strength of the component are better evaluated.

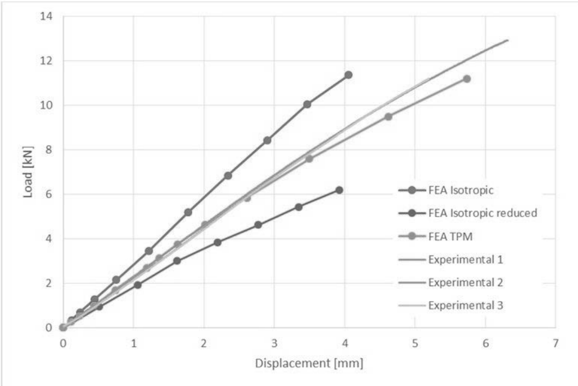


Fig. 11: Comparison of the experimental load-displacement curve for longitudinal injection with results obtained by FE with an isotropic material and FE with TPM

Comparison of isotropic and anisotropic models is not meaningful in the case of the other injection-molding configurations, since the isotropic models are insensitive to variations in the orientation patterns and to the presence of weld lines. In spite of the excellent agreement between TPM simulations and experimental results presented here, the analysis of injection-molded parts containing weld lines is still an open issue. In fact, for similar simulations conducted with other fiber-reinforced materials, we observed greater differences between the numerical and the experimental results. More investigation into the simulation of the mechanical behavior of weld lines, based on accurate observations of their microstructure as in [5], is needed. We believe that the component presented here could be used as a demonstrator for different possible solution techniques in the future.

Conclusion

In this paper we presented the design of an injection-molded ribbed beam to be used as a demonstrator for different modeling techniques. The demonstrator is designed to be injection-molded using different combinations of injection channels and gates, thus enabling different fiber orientation patterns to be obtained and the position of weld lines to be varied.

The beam was tested under four-point bending and the tests were simulated by TPM, that is, by combining process simulation with structural analysis. The results of the simulations were in good agreement with experimental results and constitute an improvement over simplified modeling techniques, such as those assuming an isotropic material.

Bibliographic references

[1] Bernasconi A, Davoli P, Basile A, Filippi A. Effect of fibre orientation on the fatigue behaviour of a short glass fibre reinforced polyamide-6. *International Journal of Fatigue* 2007, 29: 199–208.

[2] Castagnet S, Nadot-Martin C, Bernasconi A, Lainé E, Conrado E, Caton-Rose P. Through-Process Modeling for the fatigue life assessment of notched injection-molded specimens, 16th European Conference on Composite Materials (ECCM 16), Seville, Spain, (2014).

[3] Moesenbacher A, Brunbauer J, Pichler P, Guster C, Pinter G. Modeling and validation of fatigue life calculation method for short-fiber-reinforced injection moulded parts. In: ECCM 16; 2014; Seville.

[4] Guster C, Pinter G, Mösenbacher A, Eichlseder. Evaluation of a simulation process for fatigue life calculation of short-fiber-reinforced plastic components. *Procedia Eng* 2011;10:2104-2109.

[5] Ayadi A, Nouri H, Guessasma S, Roger F. Large-scale x-ray microtomography analysis of fiber orientation in weld lines of short glass fiber reinforced thermoplastic and related elasticity behavior. *Macromol. Mater. Eng*. 2016, DOI: 10.1002/mame.201500463.

Surface quality: improving the quality perception of molded parts

PhD candidate **P. Gamonal-Repiso**, Dr. **J.M. del-Mazo**,
SEAT S.A, Martorell, Spain;
Prof. Dr. **M. Sánchez-Soto**, Centre Català del Plàstic/Universitat Politècnica de Catalunya-BarcelonaTech, Terrassa/Barcelona, Spain

Abstract

A novel assessment method based on three-dimensions technology has been proposed for analyzing the surface quality of injection-molded parts. Starting from a mold having a leather texture engraved on it, the quality of replication on the surface of a polypropylene molded part has been studied as a function of the injection parameters. In order to establish a relationship between quality appearance and surface topography, amplitude parameters and functional parameters have been compared. A white light interferometer (WLI) was used to assess the surface and a scanning electron microscope (SEM) was employed to detect small features on the surface. The results indicated that, in terms of quality perception, functional parameters are more accurate than amplitude parameters for quantifying the mold replication on the polypropylene surface.

1. Introduction

Quality appearance is of great importance in the production of automotive interior parts, being strongly connected with quality perception. The uniformity and interior harmony are the main goals to be achieved since surface differences between adjacent components gives the customer an impression of low quality.

Nowadays, the method used for assessing the surface appearance is based on subjectivity and two-dimensional measurements [1]. However, this method does not provide enough surface information and requires several optimization loops in order to obtain optimal matching between components. A novel surface assessment method based on three dimensions (3D) is therefore necessary to adequately guarantee that the surface appearance of each component will meet requirements.

Achieving the aims of the new method requires standardization of surface assessment. A suitable setting of several parameters, such as sampling area (A), sampling length (Δx, Δy) and number of data points (N, M), is required for each kind of texture. Several studies have been made relating to surface topography and surface appearance – for example, Ignell [2] compared surface topographic features with gloss variations using a stereographic scanning electron microscope (SEM). In an earlier work, Ariño [3] characterized the surface of molded parts using alternative spatial parameters instead of traditional roughness parameters. Spatial parameters were a likely approach to relate surface appearance to surface topography. In the present study, the interferometry technique is used to characterize the surface. Interferometry is based on adding and cancelling amplitudes of different waves with the same frequency. With this technology a three-dimensional map of the surface can be built up.

2. Experimental

Materials:

The material used was a polypropylene with 5% talc (PP-TD5). This is a commercial injection-molding grade for automotive interior applications produced by BASELL S.L (Tarragona, Spain) and denoted HC TKC 2007 N. The material had a density of 0.93 g/cm^3 (ISO 1183-1/A) and a melt flow rate (230 ºC, 2.16 kg) of 16 g/10 min (ISO 1133).
The mold cavity was a square with dimensions 100 x 100 x 3 mm (length x width x thickness) having a fan gate in one of the sides to minimize gating effects.
The cavity surface was engraved by Standex S.A (Barcelona, Spain) with a leather texture by means of a chemical process.

Injection trials:

The samples were molded using an injection machine, the Engel Victory 110, with a clamping force of 1100 KN.
A design of experiments (DOE) was carried out to analyze the effect of injection parameters on surface appearance. A factorial design at three levels (low, intermediate, high) was carried out (3^2) where the factors were the melt temperature (T_{melt}) and mold temperature (T_{mould}). Inside each temperature block, holding pressure was varied at two levels (400-600 bar) and injection speed was varied at three levels (100-300-500 cm^3/s). A total of 54 runs was made (Table 1). The injection parameters were selected according to the process window.

Table 1: Injection parameters and their levels

Block	T°melt (°C)	T° mold (°C)
Low temperatures	200	30-50-80
Intermediate temperatures	235	30-50-80
High temperatures	270	30-50-80

<u>Standardization of sampling conditions:</u>

Standardization of the sampling conditions was based on the Nyquist theorem, which provides the frequency limits (eq. 1, 2) (high frequency and low frequency).

$$f_h = \frac{1}{2\Delta x} = \frac{1}{2\Delta y} \qquad (1)$$

$$f_L = \frac{1}{Nx\Delta x} = \frac{1}{My\Delta y} \qquad (2)$$

Where f_h is the high frequency limit, f_L is the low frequency limit, N and M are the number of data points on the *x* and *y* axes. Δx, Δy are the sampling intervals on the x and y axes.

The sampling area was square, so the sampling parameters were set at N = M and $\Delta x = \Delta y$. The size of the sampling area and sampling length were normalized via the following strategy. The number of data points was set at 2048 since this provides the highest resolution ($\Delta x = \Delta y = 0.001$ mm) for the 2.08 x 2.08 mm area. Moreover, as the fast Fourier transform (FFT) was applied, a data length of a power of two, that is, 2^p (for the MxN matrix, $2^p x 2^q$, p,q=1,2,…) was preferable. The sampling length was varied from 0.001 mm to 0.02 mm (Table 2). Consequently the size of the area was obtained using Equation (3).

$$A = lx \cdot ly = (M-1)\Delta x \cdot (N-1)\Delta y \quad (3)$$

where *A* is the area and *lx, ly* are the lengths on the *x* and *y* axes.

Once the sampling area was established, the same procedure was carried out to find the optimal sampling interval, as seen in Table 3.

The data were processed with the FFT, which transferred the data points from the space domain into the frequency domain. A Butterworth bandpass filter (Eq. 4) was then applied in order to discard the frequencies which were outside the frequency limits (high frequency and low frequency).

$$F(f) = 1 - \frac{1}{1+\left(\frac{f \cdot f_b}{f^2 - f_c^2}\right)^{2n}} \qquad (4)$$

where f is the frequency, f_b is the bandwidth, f_c is the cut-off frequency and n is the filter order, which describes the steepness of the filter.

In the current study, the following considerations have been taken into account in order to filter data acquisition:

- The cut-off frequencies were the low-frequency and high-frequency limits.
- The filter order, n, was set at 1.

Surface characterization

Surface characterization in 3D has been carried out comparing height parameters and functional parameters:
The height parameters are the following: average roughness (Sa) (Eq. 5), root mean square roughness (Sq) (Eq. 6) and ten-point height (Sz) (Eq. 7).

$$S_a = \frac{1}{A} \iint |z(x,y)|\, dxdy \qquad (5)$$

$$S_q = \sqrt{\frac{1}{A} \iint Z^2(x,y) dxdy} \qquad (6)$$

$$S_z = \left(\sum_{L=1}^{5} |P_{i\,max}| + \sum_{L=1}^{5} |V_{i\,max}|\right)/5 \qquad (7)$$

The functional parameters are the following: material ratio (mr) and material volume (Vm).
The material and volume ratios are the material forming the surface from the height corresponding to a threshold value to the highest surface peak (Figure 1). The threshold was set at 120 µm in order to analyze the amount of material located above the threshold height.
The material ratio was calculated via the bearing area curve, and the material volume was calculated using the *Mark III* software program.

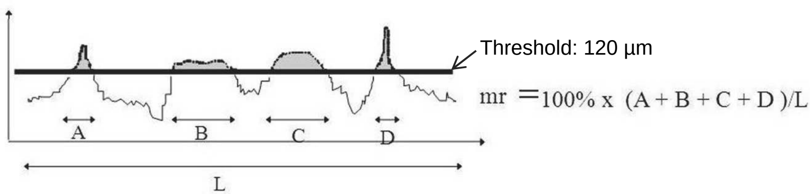


Fig. 1: Material ratio calculation. [5]

3. Results and discussion

Sampling conditions:

Figure 2 shows the influence of the sampling area on high parameters: Sa, Sq and Sz. Surface topographic information increases proportionally with the size of the sampling area from 4.16 to 419.02 mm^2, at which point a plateau is reached. Further increments in the measurement area do not provide any additional information. From this point of view then, an area of 419.02 mm^2 (20.47 x 20.47 mm) is the optimal size for carrying out the analysis (Trial D in Table 2).

Table 2: Trials for determining the sampling area

Trial	Area (mm^2)	Nx = My	$\Delta x = \Delta y$ (mm)	High frequency (mm^{-1})	Low frequency (mm^{-1})
A	4.16	2048	0.001	500	0.50
B	16.73	2048	0.002	250	0.25
C	104.65	2048	0.005	100	0.10
D	419.02	2048	0.01	50	0.05
E	1676.08	2048	0.02	25	0.025

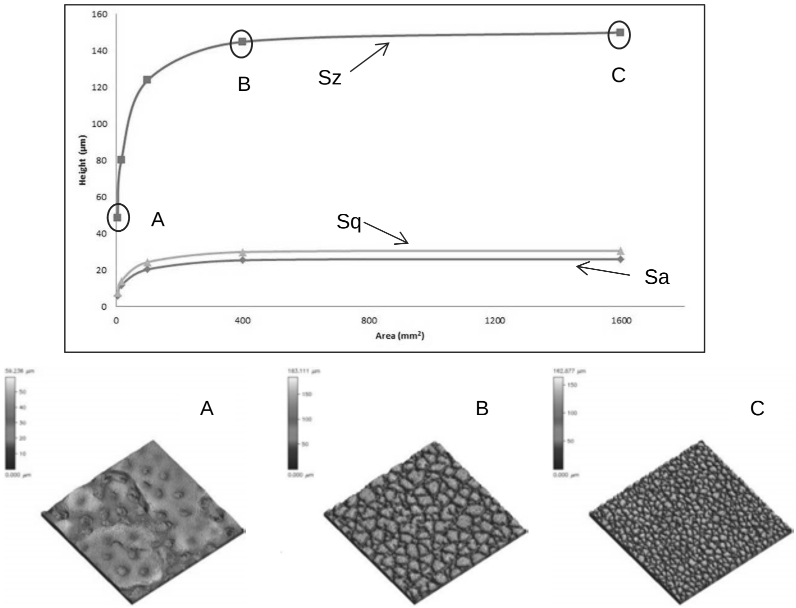


Fig. 2: Sampling area influence on high parameters: Sa, Sq and Sz.

The optimal size of the sampling area is 20.47 x 20.47 mm (Figure 2B), which provides the same information about the surface as does a larger area of 40.94 x 40.94 mm (Figure 2C). Moreover, it can be seen that Figure 2A fails to provide enough topographic information.

On the other hand, the optimal sampling length for assessing an area of 20.47 x 20.47 mm is 0.02 mm (Trial C in Table 3), as shown in Figure 3B. The same topographic information was obtained with less evaluation time than when a shorter sampling length was set (Figure 3C and Table 3). Using sampling intervals greater than 0.02 mm leads to the loss of topographic information (Figure 3A).

Table 3: Trials for determining the sampling interval.

Trial	Sampling interval Δx, Δy (mm)	Nx = My	High frequency limit (mm^{-1})	Low frequency limit (mm^{-1})	Evaluation time (min)
A	0.005	4096	100	0.048	270
B	0.01	2048	50	0.048	75
C	0.02	1024	25	0.048	30
D	0.05	410	10	0.048	10
E	0.10	206	5	0.048	5
F	0.20	104	2.5	0.048	2
G	0.50	42	1	0.048	1

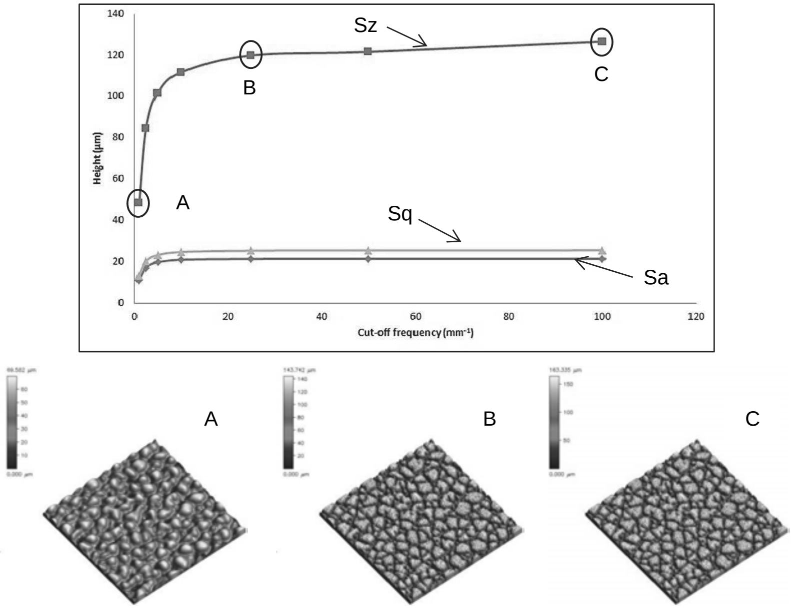


Fig. 3: Sampling interval influence on topographic information.

The optimal sampling conditions, from the point of view of automotive applications, are shown in Table 4.

Table 4: Optimal sampling conditions for leather grain.

Area (mm^2)	Nx = My	$\Delta x = \Delta y$ (mm)	High frequency (mm^{-1})	Low frequency (mm^{-1})	Evaluation time (min)
419.02	1024	0.02	25	0.048	30

<u>Relation between injection parameters and surface:</u>

The surfaces have been evaluated while taking into account high parameters (Sa, Sq and Sz) and functional parameters (mr and Vm), as previously stated.

The results obtained did not show significance variations in the Sa and Sq parameters. In all analyzed surfaces the mean values for each parameter were very similar at 25.5 ± 0.1 µm and 29.9 ± 0.1 µm respectively.

On the other hand, small differences were detected for the Sz value, which, depending on injection parameters, varied from 136 µm to 150 µm. The most important injection parameters for obtaining the highest roughness value were melt temperature (T_{melt}), mold temperature (T_{mold}) and holding pressure (P_{hold}). These injection parameters lead to a better replication of the mold surface by the polymer melt. However, mold reproduction on the plastic surface is difficult when working at low temperatures since the polymer melt freezes very quickly without having enough time to reproduce the mold texture. In addition, a low injection speed and holding pressure result in poor mold replication on the polymer surface.

Table 5: Injection parameters to achieve the highest and lowest Sz value.

Sz (µm)	Tmelt (ºC)	Tmold (ºC)	Phold	V iny
150	270	80	600	100
136	200	30	400	100

Greater differences were found with the mr and Vm parameters. The material ratio difference was from 19.40% to 33.64%. Moreover, material volume changed from 4.72×10^9 μm^3 to 9.12×10^9 μm^3. Variation in both the material and volume ratios represents a greater quantity of polymer above the 120 µm threshold height, and thus more accurate mold replication was achieved by the polymer melt.

Figures 4 and 5 show the results for the maximal and minimal material ratio values, and the injection conditions that deliver that replication. The highest mr value was reached at the maximal level of mold temperature, holding pressure and injection speed as well as the minimum melt temperature. This latter factor was unexpected but can be explained by the high MFI (16 g/10 min) of the polypropylene grade used. Selection of high melt temperatures leads to the appearance of flashing around the sample, resulting in a final lower replication of the mold surface. On the other hand, low melt temperatures prevent polymer flashing and all the pressure exerted during injection is transferred to the melt material and to the mold's leather-textured surface.

Table 6: Injection parameters for achieving the highest and lowest mr values.

mr (%)	Tmelt (ºC)	Tmold (ºC)	Phold	V iny
33.64	200	80	600	500
19.40	200	30	400	100

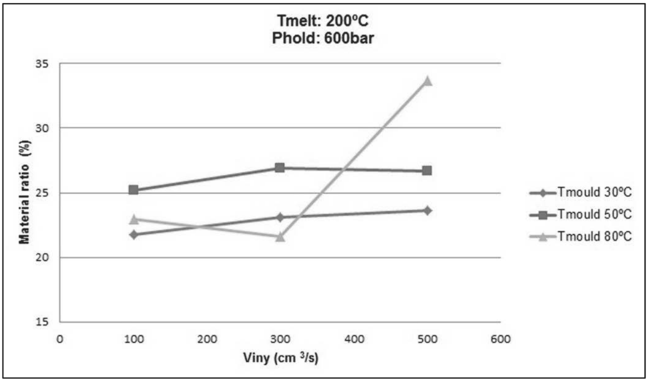


Fig. 4: Injection conditions to reach the highest mr value

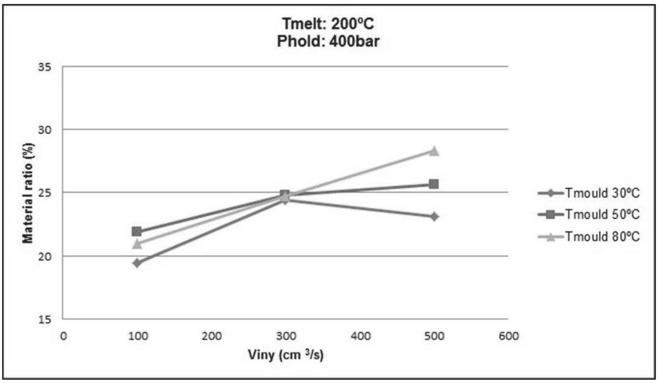


Fig. 5: Injection conditions for reaching the lowest mr value

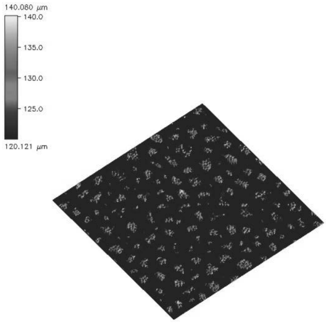


Fig.6: T_{melt}: 200ºC; T_{mold}: 30ºC;
V_{iny}: 100cm^3/s P_{hold}: 400bar
Sz: 136.601µm; mr: 19.4%;
Vm: 4.72x10^9 µm^3

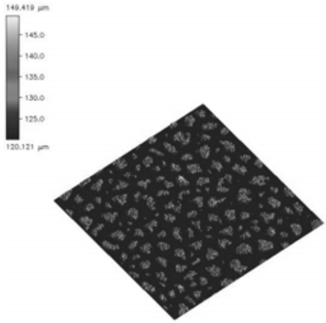


Fig.7: Tmelt: 200ºC; Tmold: 80ºC;
Viny: 500cm^3/s; Phold: 600bar.
Sz: 144.731µm; mr: 33.64%;
Vm: 9.12x10^9 µm^3

Figures 6 and 7 represent the quantity of material above the 120 µm threshold height. A comparison reveals that the injection conditions in Figure 7 result in a proper filling of the micro-cavities of the leather texture. The material ratio and material volume indices exhibit significant differences.

The samples with highest mr and Vm values have the best accuracy of mold replication although not showing the greatest roughness (Sz). This means functional parameters are more adequate than amplitude parameters for assessing mold reproducibility by the polymer melt. Figure 8 represents the replication accuracy of the mold texture on the polymer surface.

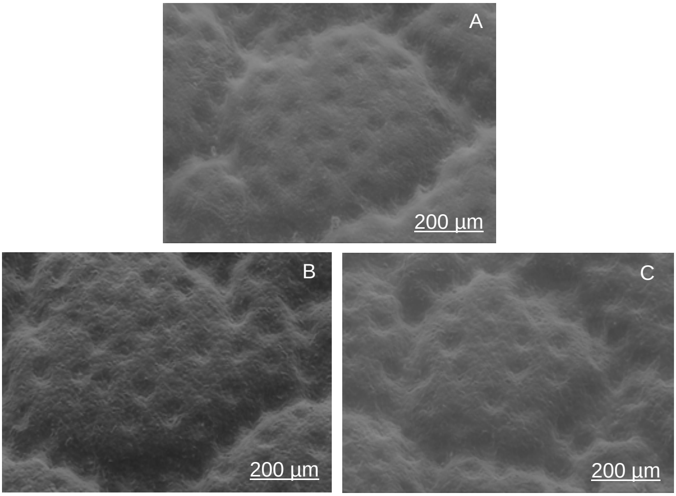


Fig. 8: Scanning electron micrographs of PP surface. Sample A: Sz: 136.601µm; mr: 19.4%; Vm: 4.72×10^{9} μm^{3}. Sample B: Sz: 144.731µm; mr: 33.64%; Vm: 9.12×10^{9} μm^{3}. Sample C**:** Sz: 150.517µm; mr: 26.31%; Vm: 7.27×10^{9} μm^{3}

Although Figure 8B is not the sample with the highest roughness value (Sz), it does have the maximal mold surface replication, having surface microfeatures absent in samples A and C.

4. Conclusions

The sampling conditions, sampling area and sampling interval have an important influence on topographic information.

Injection parameters can modify the mold reproducibility on the polymer surface.

In order to characterize the surface from the point of view of mold replication, functional parameters have been demonstrated to be more accurate than amplitude parameters.

This study demonstrates the need for a standardized procedure in the sampling conditions for textured surfaces in automotive applications.

5. Acknowledgments

The authors thank BASELL S.L (Tarragona, Spain) for supplying the material, and Standex S.A (Barcelona, Spain) for engraving the mold surface and for technical support.

6. References

[1] DIN EN ISO 4287: 1998

[2] Ignell, S.: Three-dimensional scanning electron microscopy characterization of the topography of textured polymeric surfaces. *Polymer engineering and science*, 50 (2010) 8pp. 1527-1534.

[3] Ariño, I.: *S*urface texture characterization of injection-molded pigmented plastics. *Polymer engineering and science*, 44 (2004) 12 pp. 1615-1626.

[4] Lehmann, P.: *Fundamental aspects of resolution and precision in vertical scanning white-light interferometry*. IOP Publishing, 4 (2016) .

[5] Cohen, D. K. *Michigan metrology*. LLC*,* USA: 2014.

[6] Stout, K. J, *Development of Methods for the Surface Characterization of Roughness in Three Dimensions*. Penton Press, London: 2000.

[7] Muralikrishnan, B. and Raja, J. *Computational surface and roundness metrology.* Springer, USA: 2009.

[8] Thomas, T. R. *Rough Surfaces*. Imperial College Press, London: 1999.

[9] Whitehouse D. J. *Handbook of Surface Metrology*. Institute of Physics Publisher, Bristol and Philadelphia: 1994.

Lightweight design at Volkswagen

Via thermoset pultrusion to the production of fiber-reinforced plastics for a load path in the door structure with high-volume production potential

Dr.-Ing. **P. Hörmann**, Dipl.-Ing. (FH) K. **Bornemann**,
Dr.-Ing. **F. Flueggen**, Dipl.-Ing. H. **Herten**,
Dr.-Ing. V. **Hohm**, Dr.-Ing. T. **Ströhlein**,
Volkswagen AG, Wolfsburg

Abstract

This contribution focuses on the application of thermoset pultrusion for a cost-effective production with high-volume capability of fiber-reinforced plastics (FRP) in the mid-size car segment at Volkswagen. In addition to thermoset pultrusion as a process, a description is also given of an iterative approach consisting of component design, numerical validation and final experimental testing for the development of a so-called FRP door sill tube. One significant result is success in passing a small-overlap crash test. This qualifies the FRP door sill tube for a series application.

1. Introduction

Lightweight construction is made possible by the intelligent combination of different materials and their properties [1]. The advantages and disadvantages of fiber-reinforced plastics (FRP) are known in the context of an application in automotive engineering. With respect to their low density, fiber-reinforced plastics possess superior material properties in the direction of the fiber: strength and stiffness. Nevertheless fiber-reinforced plastics have not yet succeeded in breaking through commercially as regards an automotive high-volume application.
The cost intensity of the semi-finished products and the lack of robust, fully automated processes weigh too heavily here.

2. Thermoset pultrusion for automobile manufacturing

Thermoset pultrusion combines material-specific advantages with the unique differentiator of a robust, continuous and fully automated production process. With process speeds up to 3 m/min in combination with cost-effective semi-finished product concepts it meets the requirements of automotive mass production.

The title of this article raises the following questions:

1. Why choose a thermoset rather than a thermoplastic matrix?
2. Why choose pultrusion technology as the manufacturing process?
3. The technology has been well established in other industries for many decades and TÜV-tested components are produced, for example, for the construction industry. Where is the challenge in using this technology for automotive applications?

In the automotive industry, the focus is mainly on thermoplastic matrix systems for making FRP components for future applications [3, 4, 5]. The costs for FRP components correlate strongly with the speed of the process. If a target quantity per time unit is not achieved with a production unit, that unit, together with the tooling, must be duplicated.

The direct consequences are high investment costs, as well as a marked scatter in component quality.

Compared to thermoplastic fiber composite structures, the use of thermoset plastics means that structural parts can be produced which can support even higher loads. When combined with thermoset pultrusion, faster processing speeds can be achieved than with thermoplastic manufacturing technologies.

This high process speed and the resulting low production costs answer the question as to why pultrusion technology was chosen as the manufacturing process. In addition, the very satisfactory mechanical properties which can be achieved in a restricted installation space and the low material costs resulting from the technology also speak in favor of pultrusion. A detailed description of the process may be found in [6]. The high mechanical properties are achieved by maximizing the fiber volume content to values above 70% and by implementing an ideally stretched arrangement of the most heavily stressed fibers. A major proportion of this heavily loaded fiber material can be taken straight off the reel as a roving and incorporated in the final product. This direct processing means that the maximum economic potential of the costly fiber material can be exploited without the need for upstream processing steps.

Additional semi-finished products enable continuous processing to create a fiber hybrid by using different fiber types and varying the fiber orientation.

The question regarding the challenge in an automotive application is more difficult to answer. Pultrusion technology is already established in door and window construction, concrete reinforcements, the wind energy sector and in the form of structural components in the construction industry. Why, despite their potential, have no pultruded components so far found application in the automotive sector?
The hurdles standing in the way of establishing a new technology such as pultrusion in automotive high-volume production are less well-known. One of the obvious challenges lies in the complex component geometries involved in an automotive application. Technology-related 'design rules' must be known at an early stage of component development and be taken into account. With regard to cost-effectiveness, highly stressable profile structures can be produced. Changing a cross-section longitudinally is, however, only possible with marked losses in process speed and with increases in manufacturing complexity.
The material system which is to be processed must satisfy the demands of an inexpensive, fully automated, robust and low-waste production. Defined mechanical load cases are to be satisfied globally and be predictable in the context of a validated numerical design. These requirements differ significantly from those of the branches of industry we have mentioned in which components are mainly bound to a particular location and are stationary in use.

Figure 1 shows in simplified form the correlation between annual production quantities and unit cost for three manufacturing technologies: manual or semi-automated pre-preg processing, resin transfer molding (RTM) and pultrusion. With pultrusion technology, the comparatively low unit costs make it possible to produce fiber composite materials economically and with high-volume capability for a mid-range vehicle segment: annual production quantity in excess of 100,000 units.

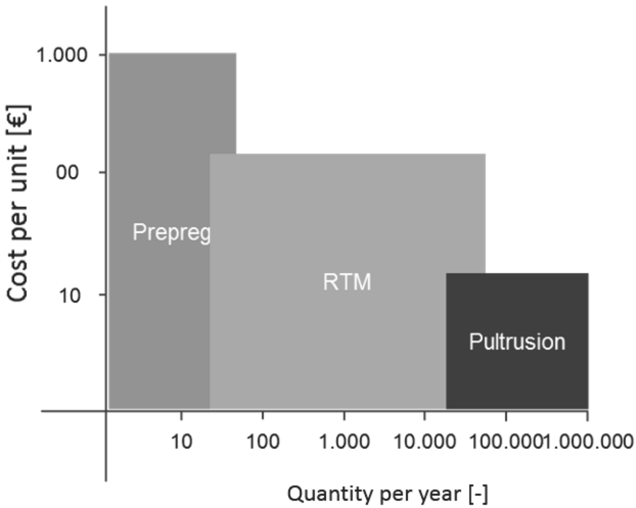


Fig. 1: Simplified correlation between unit costs and annual production quantities of three manufacturing technologies for components made of fiber-reinforced plastic

3. Door sill tube made of fiber-reinforced plastic

With thermoset pultrusion it is possible for the first time to replace a conventional steel crash-tube acting as a load path in the door structure with a so-called door sill tube made of fiber-reinforced plastic (FRP TBR) (see Figure 2). Volkswagen uses this load path to give the customer better protection in frontal impact scenarios, such as, for example, the small-overlap collision.

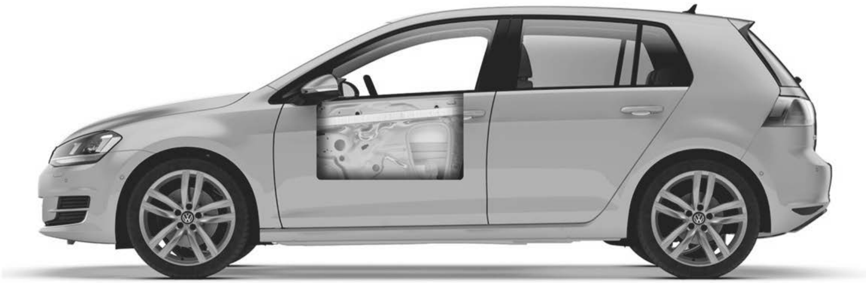


Fig. 2: Golf 7 showing an example of a so-called door sill tube made of fiber-reinforced plastic as a door load path

The FRP TBR is a fiber hybrid. Its layered structure is shown in cross-section in Figure 3. The 0° direction is the direction of manufacture and in the event of a frontal crash with small overlap is the main direction of loading. The carbon fibers are oriented in this for onward transmission of the compressive loads which occur. In the 90° direction, transversely to this, there are glass fibers which in the external part of the cross-section act as a corset to prevent the carbon rod from buckling and in the internal part protect against corrosive influences in the wet area of the vehicle. More than 90% of the carbon fibers exposed to compressive loading are transferred into the component as a roving directly off the reel, rendering unnecessary a cost-increasing intermediate stage involving semi-finished products. The glass-fiber sheathing uses semi-finished products. Thermoset pultrusion makes cycle times of 20 seconds possible.

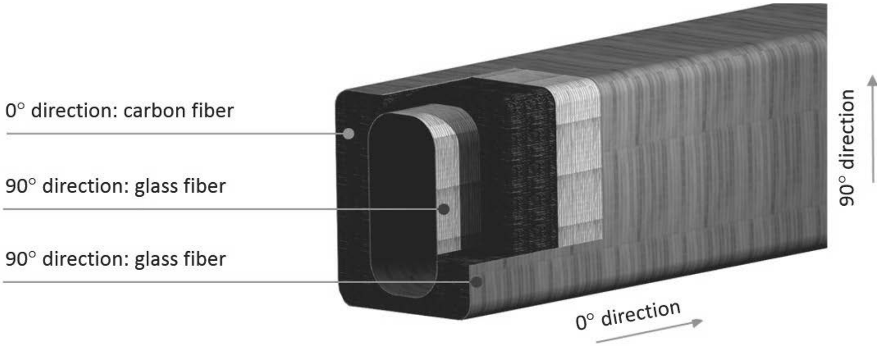


Fig. 3: Laminate structure of a so-called door sill tube made of fiber-reinforced plastic

The FRP TBR is designed to ensure occupant protection in front-crash scenarios when there is only a small overlap of the body and the obstacle. One challenge here is that the structures in the center of the vehicle cannot act to absorb emerging forces or to pass them on into the rear of the vehicle (see Figure 4).

In order to meet these requirements, Volkswagen provides a third load path via the door. As the current series-production solution a steel crash tube in interaction with the door sill and roof frame structure transmits forces from the A pillar via the B pillar into the rear part of the vehicle. It should be emphasized that the forces occurring are passed on and not reduced. It is not intended that energy be absorbed.

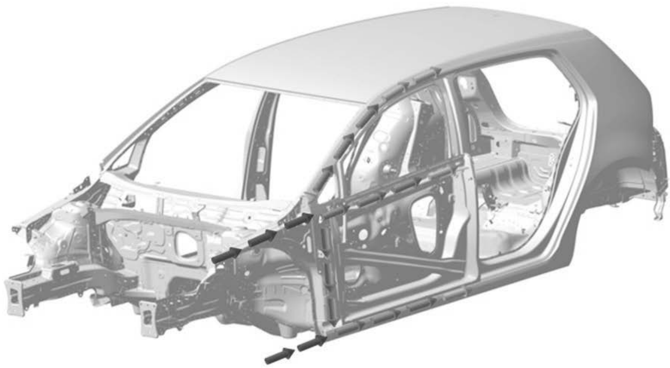


Fig. 4: Computer-aided design model of the bodywork shell of a Golf 7 with examples of load paths during a small-overlap front crash.

A steel crash tube (see Figure 5 left) makes a weight saving of about 40% possible in comparison with concepts which only aim at strengthening the roof frame or the sill.
In comparison with the steel crash tube, the FRP TBR delivers a weight saving of 50% (see Figure 5 right). So-called plastic-encapsulated aluminum end pieces are defined for introducing into the FRP TBR the forces which occur and passing them through it and onward (colored yellow in the diagram). The end pieces are pressed into the FRP tube, being friction-locked by an interference fit. As regards the design of this hybrid component and its sub-components, there is a challenge in harmonizing the different materials – glass and carbon fiber, matrix material, aluminum and plastic encapsulation – with regard to handling mechanical loads and their introduction, thermal expansion, corrosion, and fits. All sub-components and the assembly are manufactured by robust processes with volume-production capability.

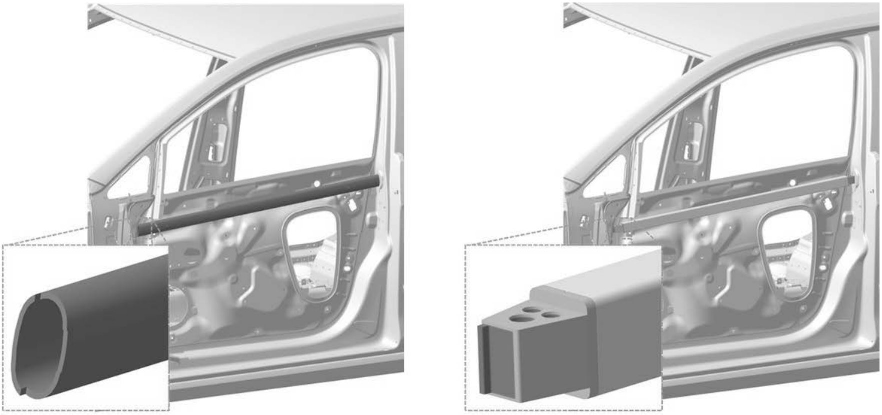


Fig. 5: Computer-aided design model of the door shell of a Golf 7 with a steel crash tube as load path (left) and a door sill tube made of fiber-reinforced plastic (right)

4. Validation

The component design was validated among other things numerically by vehicle crash simulation, experimentally by dynamic component testing in a drop-tower rig and a real car crash.

The FRP material was characterized for numerical validation to make a virtual description of material behavior possible via suitable material models for the simulation software in question.
The material tests required were carried out separately for glass- and carbon-fiber-reinforced test pieces. The material characterization of pultruded test pieces ensured comparability with respect to fiber orientation, fiber volume content, and so on. It was carried out for different temperatures.
The material behavior of the aluminum and the plastic encapsulation for the end pieces had already been characterized in the context of other projects.

From the resulting force/displacement or stress/strain curves, the corresponding input data for numerical simulation were generated in collaboration with AUDI AG. The stress/strain curves in Figure 6 show the subsequent validation of numerical material behavior using experimental data for the glass-fiber- and carbon-fiber-reinforced plastic (GRP and CFRP). A comparison shows a very good correlation in this example.

This approach makes possible not only a holistic understanding of the material but a cost-efficient validation requiring little prototyping on account of the realistic component design.

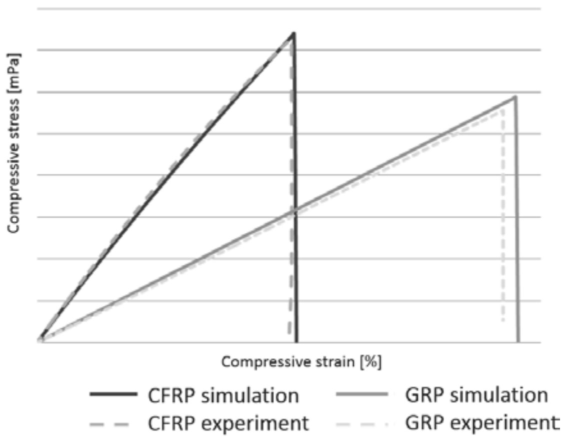


Fig: 6: Stress/strain diagram – compressive loading – resulting from the experimental material characterization and simulation of a glass-fiber-reinforced and a carbon-fiber-reinforced plastic

For experimental validation the FRP TBR was tested dynamically in a drop tower test. The test rig is illustrated in Figure 7. Here the FRP TBR was fixed in a vertical position in a drop tower. Metal stacks were positioned at a little distance at each end of the FRP TBR As regards material alloys, sheet metal thickness combination and orientation, these corresponded to the installation situation at the A and B pillars in the vehicle shell.

A defined weight falls from a defined height onto the FRP TBR and compresses it. The crash energy input and the deformation rates corresponded to those of a real vehicle small-overlap crash. The aim was for a defined force level equivalent to the steel crash tube to be transmitted for a defined period of time from the A pillar to the B pillar. This was carried out successfully and in a final step resulted in a pass for a real small-overlap crash in a Golf 7.

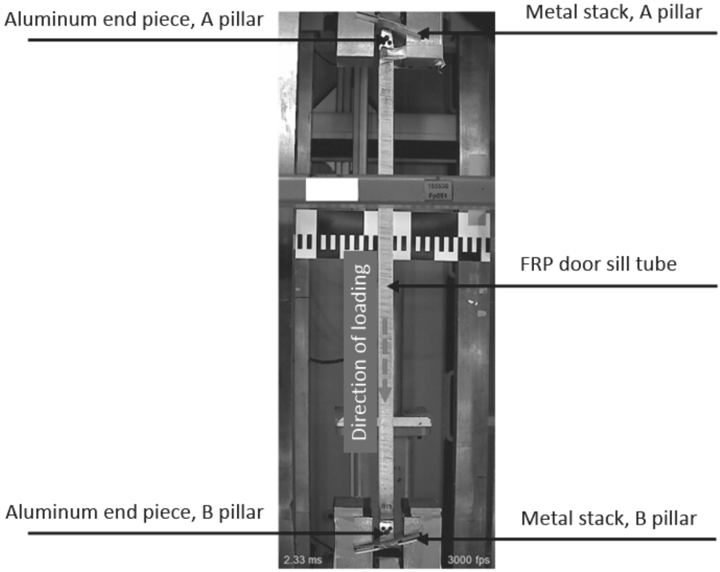


Fig: 7: A drop tower test for dynamic testing of a so-called door sill tube made of fiber-reinforced plastic

5. Summary and outlook

This contribution focuses on the application of thermoset pultrusion for a cost-effective production with high-volume capability of fiber-composite materials in the mid-size car segment at Volkswagen.

For the first time a conventional steel crash-tube acting as a load path in the door structure is replaced by a so-called door sill tube made of fiber-reinforced plastic. In comparison with the series solution a weight saving of around 50% is achieved with the FRP TBR as a thermoset fiber pultrudate while incurring only single-digit costs.
It combines material-specific advantages with the unique feature of a robust, continuous and fully automated manufacturing process: thermoset pultrusion. Process speeds of up to 3 m/min in combination with cost-effective semi-finished product concepts and a targeted choice of fibers satisfy the requirements of automotive high-volume production.

In addition to thermoset pultrusion as a manufacturing process, a description is also given of an iterative approach consisting of component design, numerical validation and final experimental testing of the FRP door sill tube. One significant result is success in passing a small-overlap crash test. This qualifies the FRP door sill tube for a series application.

A focus of future work will be the numerical description of the strain-rate-dependent material behavior of the composite fiber material. A highly dynamic loading of the fiber-reinforced plastic leads to a significant increase in mechanical performance. Both strength and elongation at break increase due to visco-elastic effects in the plastic matrix [7, 8] as compared with a quasi-static load.
This performance improvement will be taken into account in future in the design of the component and subsequent numerical validation. This approach offers the possibility of further economic upgrading by an even more precise, slimmer design of the FRP TBR.

Other work points before final integration in a production vehicle are the qualification for high-volume production of a joint concept for integration into the vehicle body shell and also an increase in processing speed by means of a combination of different production technologies.

6. Bibliography

[1] VDI-Gesellschaft Material Engineering, Werkstoffinnovationen für nachhaltige Mobilität und Energieversorgung, 2014.

[2] A. Knoch, “Herausforderung Großserie”, Frankfurter Allgemeine Zeitung, vol. 31.10.2014, p. 0V1, 2014.

[3] Carl Hanser Verlag (ed.): Spritzgießen oder Reaktionstechnik für Automobilteile? 'Kunststoffe' 3/2013.

[4] C. Gröschel, D. Drummer: Thermoplastische Faserverbundkunststoffe. Munich, 2013.

[5] H. Eickenbusch, O. Krauss: Kohlenstofffaserverstärkte Kunststoffe im Fahrzeugbau – Ressourceneffizienz und Technologien. (VDI ZRE Publikationen: Kurzanalyse Nr. 3) Berlin, 2013.

[6] T. F. Starr, Ed., Pultrusion for Engineers. Crc Pr Inc., 2000.

[7] P. Kuhn, M. Plöckl, H. Körber. Experimental investigation of the failure envelope of unidirectional carbon-epoxy composite under high strain rate transverse and off-axis tensile loading. 11th International DYMAT Conference, 2015.

[8] H. Körber, J. Xavier, P. P. Camanho, Y. E. Essa, F. Martín de la Escalera. High strain rate behaviour of 5-harness-satin weave fabric carbon-epoxy composite under compression and combined compression-shear loading. International Journal of Solids and Structures, 2015.

Hollow profiles, organo-sheets and LFRT node structures: hybrid components made of fiber-reinforced plastics for automotive serial production

A. Liebsch, **R. Kupfer**, **M. Gude**,
Institut für Leichtbau und Kunststofftechnik,Technische Universität Dresden;
P. Müller, **N. Andricevic**,
Dr. Ing. h.c. F. Porsche AG, Weissach

Abstract

The combination of closed hollow profiles made of textile-thermoplastic composite materials with organo-sheets and their joint functionalization by injection molding presents an enormous potential for lightweight construction for highly stressed vehicle components. One major technical challenge here is the high process pressures in injection molding and the resulting stress on the hollow profiles. To prevent collapse of the hollow profiles during the filling and holding-pressure phase they must be stabilized from the inside by fluid supporting media or free-flowing particles. The present contribution presents an integrative process-structure simulation methodology for the prediction of profile deformations during injection-molding which are related to design and process.

1. Motivation

The further development of electric mobility is currently a research and development focus in vehicle construction. Here an important building block for expanding electromobility can be the systematic use of lightweight structures in the vehicles. One especially promising possibility for reducing weight is offered by highly integrative construction methods with a combination of torsionally and flexurally rigid hollow profiles as well as flat components. Substituting lightweight fiber-plastic composites (FPC) for metal materials also means that the individual construction elements can be selectively reinforced as appropriate for stress transmission, and this in turn makes further weight savings possible. Additional functionalization with injection-molding compound allows the integration of highly complex rib structures, load introduction zones and functional elements. Currently the combination of flat reinforcing structures ('organo-sheets') and injection-molding compound is already on the point of entering series production [1, 2]. On the other hand, a still considerable amount of technical design work is required in functionalizing FPC hollow profiles with molding compound before this new construction method is ready for series production [3, 4].

2. Functionalized FPC hollow profiles as innovative lightweight hybrid constructions

One technological concept for the production of functionalized hollow profiles is based on a process chain for the manufacture of complex molded topological hollow profiles (*ToHoP* process) [5]. In the *ToHoP* process, hose-shaped semi-finished items are made from thermoplastic hybrid yarns by braiding and are then combined to create a multilayer preform (Figure 1). This textile preform is then placed in a consolidation mold, with the textile architecture being allowed a high degree of flexibility as regards the bending radii and cross-section geometries which are possible. The preform is then consolidated in a variothermal inflation-hose process by means of an internal compression membrane. The use of thin-walled consolidation molds here makes for efficient process control and fabrication of the component within a few cycle times.

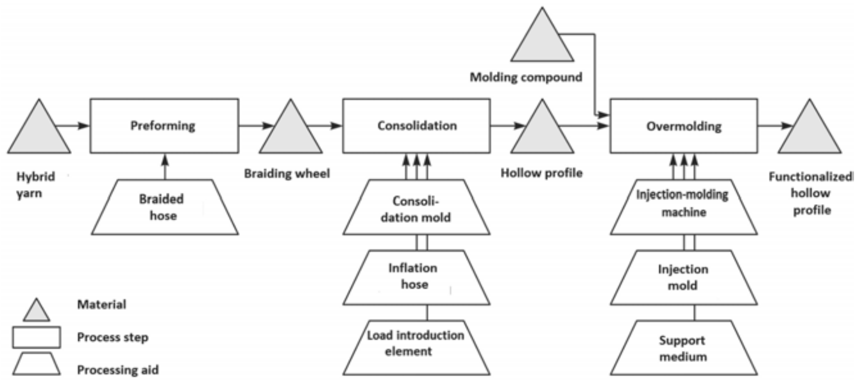


Fig. 1: Process chain for the manufacture of complex molded topological hollow profiles followed by functionalization in an injection-molding step

A comprehensive technological expansion of the process chain (Figure 1) was carried out as part of the *e-generation* [6] project funded by the Federal Ministry of Education and Research (BMBF). The consolidation process was further developed in such a way that on the one hand it became possible to integrate additional metal load-introduction elements. With a view to securing a high stress-bearing capacity of the structure as a whole, the load-introduction elements were both bonded to and mechanically interlocked with the textile-reinforced hollow profile. On the other hand, the hollow profiles produced in this way were functionalized in the next process step by being overmolded with long-fiber-reinforced thermoplastic (LFT). Here the additional structural elements such as ribs or attachment zones were attached. The Institut für Leichtbau und Kunststofftechnik (ILK or the Institute of Lightweight Engineering and Polymer Technology) of the Technical University of Dresden collaborated with Porsche AG in creating a heavy-duty technology demonstrator in the form of a car battery holder, which had previously been built as a welded steel component (Figure 2a) but was now translated into the innovative *ToHoP* injection-molding hybrid design (Figure 2b). A battery holder design was chosen which was appropriate for a fiber composite and the supporting structure was designed with the aid of a simulation. The aim was not only to achieve a marked reduction in the mass of the module while simultaneously coping with all operating stresses but also to make it easier to fit the battery in the car.

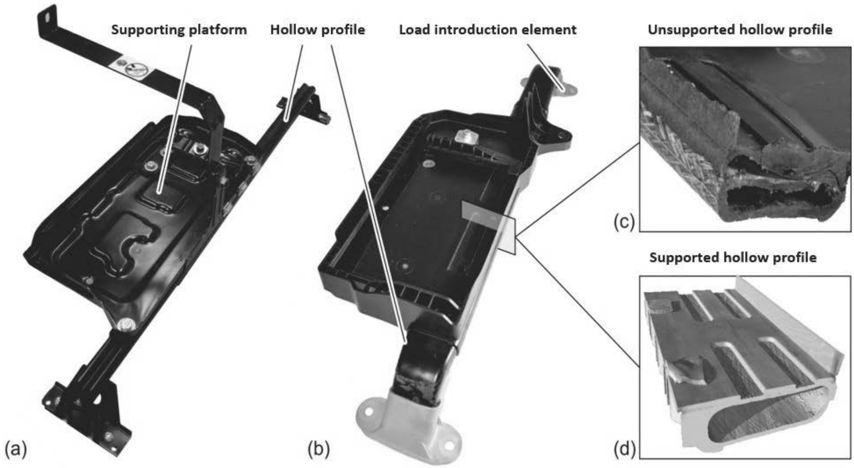
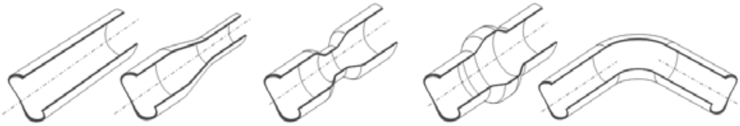


Fig: 2: Battery holder (a) in differential design using steel, (b) in integral construction as an FPC injection-molding hybrid structure with an overmolded hollow profiles (c) without and (d) with a supporting core.

The functionalization of hollow structures in the injection-molding process, unlike the back-injection molding of flat organo-sheets, calls for the use of supporting systems which stabilize the hollow profile from the inside, since even thick-walled hollow profiles can collapse under the high pressures of the injection-molding process (Figure 2c). Depending on the geometrical complexity of the hollow profile, different supporting systems can be used. Although fixed core systems can be used with hollow profiles with no undercuts or only simple undercuts, application-oriented complex geometries will require alternative supporting systems (Table 1). Within the framework of the investigations, the support system was tested with fluids and with particle-based support cores. Here stabilization using particles ensured a reproducible overmolding of hollow-profile prototypes as well as successful production of a demonstrator (Figure 2d).

Table 1: Overview of possible supporting systems for different hollow-profile geometries

Undercut	without	simple	multiple
Sketch			
Core system	solid, one-piece	solid, multiple pieces	fusible, particles, fluid

Highly dynamic tests were carried out on an acceleration sled in order to validate the functioning of the demonstrator structure with regard to ensuring the battery remains firmly attached in the event of a crash and thus satisfies the legal requirement of UN ECE R94 [7]. These tests reproduce the load cases of frontal, side, and rear collisions, with the acceleration curves being derived from complete-vehicle crash tests. The loading direction of relevance to the component design is the frontal impact, which concerns not only the acceleration curve but also the deformation kinematics of the battery holder. Since this test set-up does not reproduce the yieldingness of the vehicle body, results will always indicate a higher loading of the module than is the case in the complete-vehicle crash. Passing this test thus permits it to be said that the component has a safe design.

Figure 3 shows the FPC battery holder in the sled test for simulating a frontal collision with time increments (a) $t_1 = 0$ ms and (b) $t_2 = 40$ ms. The blue strap shown has no retaining effect on the battery but serves only as an additional safety measure. Within the context of the safety tests carried out, it was possible to demonstrate for all loading directions that the requirements relating to battery attachment were safely satisfied. No macroscopic damage to the supporting structure could be detected here which meant that the suitability of the battery holder as developed here and thus of the innovative *ToHoP* injection-molding hybrid construction was basically demonstrated for use in highly stressed structures.

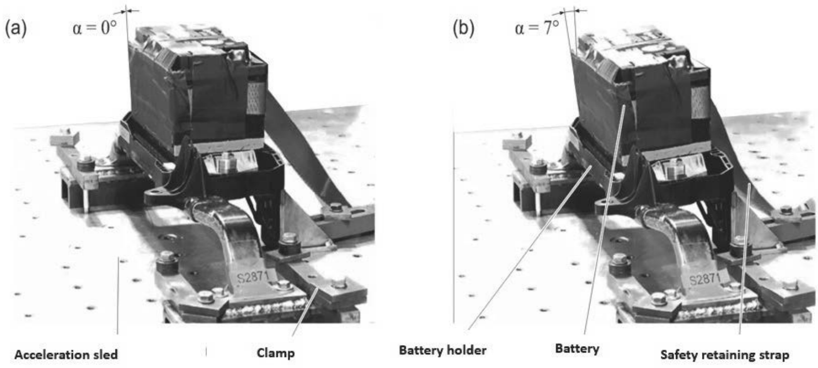


Fig: 3: Deformation of the battery holder with mounted battery in the acceleration test at (a) $t_1 = 0$ ms and (b) $t_2 = 40$ ms.

3. Experimental and numerical investigations into overmolding hollow profiles

The deepening and expansion of the process chain for manufacturing functionalized hollow profiles is currently underway as part of the BMBF-funded *FuPro* project of the *FOREL* platform [8]. Here the aim is to link together the previously separate sub-processes of making textile semi-finished products, of consolidation and of functionalization by injection molding in order to thus make possible the automated production of functionalized hollow profiles with a high-volume capability. In addition, organo-sheets should also be included in the component concept and process design as flat reinforcing structures in the sense of a semi-finished product modular system.

One of the central challenges in the process chain is functionalizing the FPC hollow profiles by injection molding on the scale of high-volume production. So far this technology has only been implemented on the prototype level. A systematic investigation into the loads acting on the hollow profile during the injection-molding process and also an analysis of the phenomena resulting when different supporting systems are used is however absolutely essential to a goal-directed design of the process. An integrative process-structure simulation as shown in Figure 4 is useful here. The transient load profiles acting on the hollow profile during the injection-molding process are captured by means of a mold-filling simulation. These load profiles can be then transferred into a structure simulation which must reproduce not only the anisotropic material behavior of the FPC hollow profile but also its structural interaction with the supporting medium.

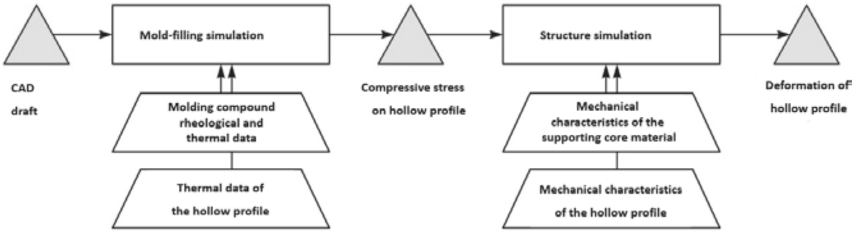


Fig: 4: Simulation scheme for the virtual analysis of hollow-profile overmolding

The feasibility of this simulation methodology is demonstrated in the example of a generic demonstrator structure (the 'Dresden rocket'). For this purpose the ToHoP process is used to make a hollow profile of variable cross-section from polyamide-6 hybrid yarn (PHP FIBERS) with a fiber volume content of 50% (Figure 5). Functionalization is carried out in a prototype injection mold which reproduces not only local ribs but also large-area binding bands and load-introduction zones in the form of screw bosses, flanges and bearing seats. An unreinforced polyamide 6/66 blend is used as the injection-molding compound (EMS GRIVORY GRILON TSS).

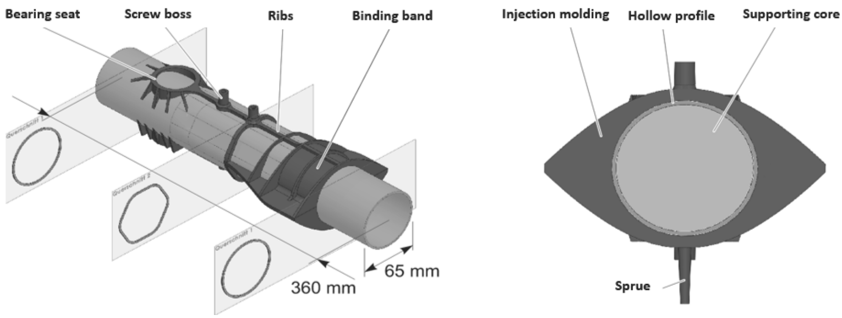
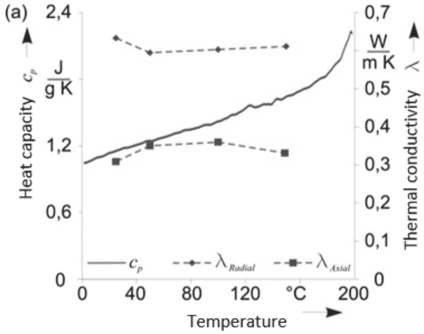


Fig: 5: CAD design of the generic demonstrator structure, the 'Dresden rocket'

The numerical mold-filling simulations were carried out with AUTODESK MOLDFLOW [9]. In addition to the injection-molding cavity, the hollow profile and also the supporting medium were modeled here as two coaxial inserts. The heat capacity and thermal conductivity were determined for the hollow profile (Figure 6) and saved as material characteristics data for the outer insert.



(b)

Property	Variable	Unit	Value
Moduli of elasticity	E_1	GPa	32,8
	E_2	GPa	9,9
Shear moduli	G_{12}	GPa	3,8
	G_{13}	GPa	3,8
	G_{23}	GPa	1,2
Transverse shrinkage	υ	-	0,2
Density	ρ	kg/m³	1,9E3
Wall thickness		mm	1,5
Laminar structure		-	±45°

Fig: 6: Material characteristics data of the hollow profile; (a) specific heat capacity from DSC measurements and thermal conductivity from hot-disk measurements; (b) mechanical properties of the hollow profile.

The highest stresses on the hollow profile are to be expected towards the end of the filling phase, which only lasts a few seconds. Due to the low thermal conductivity of the hollow profile it is assumed that no significant heat flows enter the supporting core during this brief period of time. The material physical characteristics of the supporting medium modeled in the filling simulation as a rigid internal insert are therefore ignored for the time being. The rheological properties of the injection-molding compound are taken from the program's internal database.

On this basis of this simulation model, sensitivity analyses were made of the influence of individual modeling and process parameters on the transient compressive loading of the hollow profile (Figure 7b). The pressure curve emerging from the mold-filling simulation can then be exported on a nodal basis and prepared for the structural simulation. To do so a basic model was created in the ABAQUS simulation environment [11] for the hollow profile and the contact surface of the mold cavity (Figure 7a). Here the hollow profile is discretized by shell elements (S4R). The braiding is modeled in simplified form as a bi-directional UD laminate with the material and structural properties summarized in Figure 6(b). The mold contact area (gray in Figure 7) is mapped using ideally rigid elements (R3D4). The base and end surfaces shown in Figure 7 serve alongside the shell elements of the profile structure as contact surfaces for the internal supporting media and were also modeled with R3D4 elements. A particle core and a fluid core were selected as supporting media. In the case of the particle filler, the end surface is not defined until after an initial compaction phase.

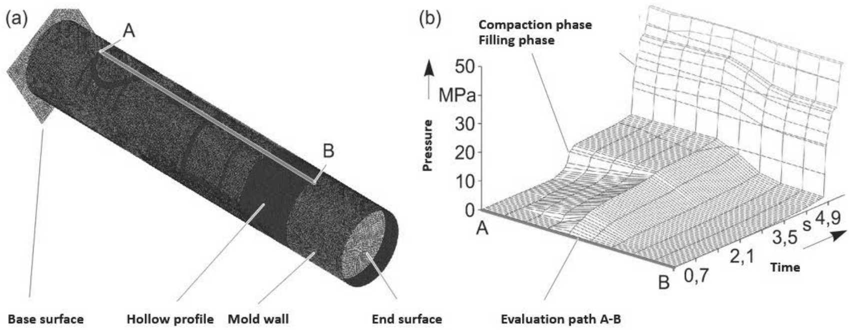


Fig: 7: (a) Basic structural model for investigating the interaction between hollow profile and supporting medium, and (b) the transient load profile along the evaluation path A-B.

The *discrete element method* (DEM) [12] was selected for modeling the particle core. Here the particles are individually modeled as ideally rigid spherical single-node elements. The yieldingness of the particle filling is reproduced via contact models. A Hertzian contact was used for the model presented here [11]. The particles have a uniform diameter of 3 mm. The material adopted was silicon dioxide (quartz) which resembled a large-grained gravel. The material characteristic values were taken from [11] and [13].

Figure 8a shows the situation at the time when the melt met the hollow profile. Due to the high local stress the particles were moved radially outward from the gate and towards the core interior. The amount of relocation here falls with increasing distance. It can also be observed that the particles are moved not only translationally but also rotationally. The friction induced between the particles causes a gradual load distribution into the particle core, which thereby exhibits load-bearing behavior similar to a solid body. The deformation of the hollow profile along the evaluation path A-B clearly reveals the local impact of the supporting effect (Figure 8b).

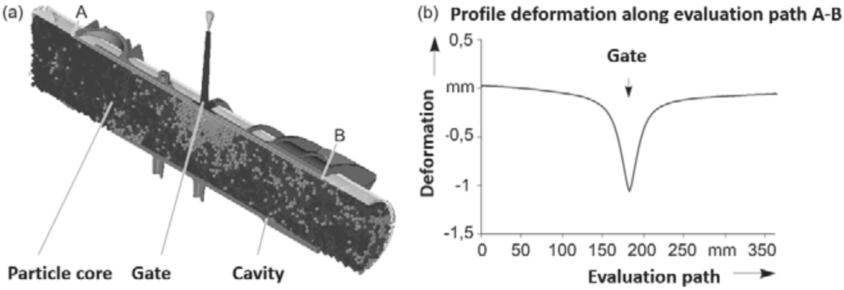


Fig: 8: Simulation results when a particle core is used. (a) Particle motion resulting from injection-molding pressure near the gate (the results from mold-filling and structural simulation are superimposed); (b) profile deformation along the evaluation path A-B.

The fluid core was modeled using the *smoothed particle hydrodynamics* (SPH) method, which is an established method for simulating the structural behavior of liquids [11, 15, 16]. Water was adopted as the fluid and is present in the hollow profile unpressurized. The necessary material characteristic values were taken from [11].

Figure 9 shows the results of these calculations, and here it is clear that the fluid exhibits fundamentally different characteristics in its supporting behavior (Figure 9a). The injection pressure acting on the surface of the hollow profile leads (in a similar way to the particle core) to local inwardly directed deformations on account of the yieldingness of the profile wall, and these are transferred to the fluid. The hollow profile, sealed off as it is at the ends, thus acts as a pressure vessel. Since water is frictionless and incompressible, the externally acting injection-molding pressure is converted into an internal pressure in the hollow profile. In the areas where the hollow profile is not supported by the mold wall outside it or by the molding compound already injected, the profile wall thus deforms in the direction of the unoccupied mold cavities. Depending on the molding pressure level and the contours of the cavity, this can lead to poor filling of the mold and even to local damage of the hollow profile.

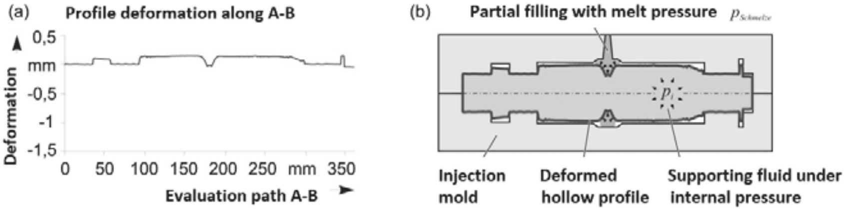


Fig: 9: Results of the structural simulation when a fluid core is used: (a) profile deformation along A-B, (b) schematic cross-section of an injection mold

4. Summary and outlook

A division of highly stressed structures into planar shear fields which pays due regard to load paths, flexurally and torsionally rigid hollow profiles, and node structures offers a high potential for lightweight construction. Due to the high anisotropy of fiber-plastic composites this material can be used for the selective reinforcement of such structures and thereby considerably raise the degree of lightweighting. Research work in this area was more intensively conducted in the past, investigating a combination of shear-resistant organo-sheets and LFT node structures and bringing this up to readiness for series production. The addition of FPC hollow profiles to this modular system does however still need a considerable amount of development work. In the BMBF-funded *e-generation* project this type of construction has for the first time been implemented in a highly stressed vehicle structure. This demonstrated its high lightweighting potential.

On the basis of the findings obtained, a process chain combining organo-sheets, hollow profiles and LFT node structures to form complex *FuPro* structures has been in development since 2015 in the *FuPro* project (Figure 10). Simulation strategies were evaluated within the framework of the project, making it possible to study the overmolding of hollow profiles in detail. The pressures acting on the hollow profile are captured with the aid of mold-filling simulations and transferred into a downstream structural simulation. With the aid of the modeling approaches of the *discrete element method* and of *smoothed particle hydrodynamics* it was possible to simulate the phenomena occurring in particle-based and fluid supporting cores. In further investigations, it will now be possible to study in detail the effects of the core properties on support behavior. In addition, the results form the basis for analyzing the interaction of hollow profiles, injection-molding compounds and flat organo-sheets in integral manufacturing process chains.

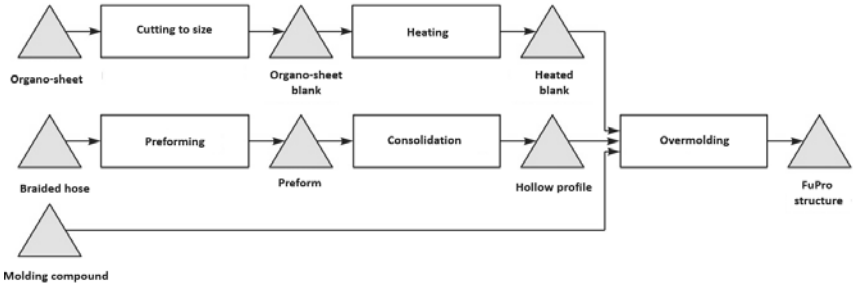


Fig: 10: Process chain for the manufacture of *FuPro* structures

Acknowledgements

The objectives underlying this report were funded by the Federal Ministry for Education and Research under grant numbers 16N11872 and 02P14Z000 – 02P14Z010. The responsibility for the content of this publication lies with the authors.

Bibliography

[1] Institut für Verbundwerkstoffe: Kombination von Thermoplast-Spritzguss und Thermoformen kontinuierlich faserverstärkter Thermoplaste für Crashelemente (SpriForm), final report on the BMBF joint project (funding period 01.11.2007 – 31.03.2011), Karlsruhe, 2011.

[2] KraussMaffei Technologies GmbH: FiberForm-Leichtbauteile, Thermoformen und Spritzgießen perfekt kombiniert, Munich, 2013.

[3] Liebsch, A.; Andricevic, N.; Maaß, J.; Geuther, M.; Adam, F.; Hufenbach, W.; Gude, M.; Batterieträger in Hybridbauweise – Kombination aus thermoplastischem Faserverbund und Aluminium ersetzt Stahlbauweise, *Kunststoffe*, No. 9, 2015, pp. 126-129

[4] Andricevic, N.: Innovativer Leichtbau bei Porsche – Batterieträger in Faserkunststoffverbund-Bauweise im Forschungsprojekt e-generation, 19th International Dresdner Lightweight Design Conference, Dresden, 19-20.06.2015

[5] Hufenbach, W.; Adam, F.; Krahl, M.; Geller, S.: Ganzheitliche Lösungsstrategien bei der Entwicklung von Faserverbundkomponenten für automobile Leichtbauanwendungen. AutoMetForm 2010, Freiberg, 24.11.2010, pp. 58-69.

[6] Institut für Leichtbau und Kunststofftechnik: Schlüsseltechnologien für die nächste Generation der Elektrofahrzeuge (e-generation), final report on the BMBF joint project (funding period 01.01.2012 - 31.12.2014), Dresden, 2014.

[7] UN ECE R94: Uniform provisions concerning the approval of vehicles with regard to the protection of the occupants in the event of a frontal collision, United Nations Economic Commission for Europe, Geneva, 2013.

[8] FOREL – Forschungs- und Technologiezentrum für ressourceneffiziente Leichtbaustrukturen der Elektromobilität, *FuPro* technology project. http://plattform-forel.de/fupro/, 09.12.2016.

[9] Autodesk, *Autodesk simulation moldflow Insight 2014*, San Rafael, California, 2014.

[10] DIN EN ISO 22007-2, Plastics - Determination of thermal conductivity and thermal diffusivity - Part 2: Transient plane heat source (hot disc method), Berlin, 2012.

[11] Dassault Systèmes, *Abaqus 6.13 Analysis User's Guide*, Providence, Rhode Island, 2013.

[12] Cundall, P. A. and Starck, O.D.: A discrete numerical model for granular assemblies, *Geotechnique,* Vol. 29, No. 1, 1979, pp. 47-65.

[13] Zhou, Y.C., Xu, B.H., Zou, R.P., Yu A.B. and Zulli, P.: Stress distribution in a sandpile formed on a deflected base, *Advanced Powder Technology,* Vol. 14, No. 4, 2003, pp. 401-410.

[14] Price, J. F.: Lagrangian and Eulerian Representations of Fluid Flow: Kinematics and the Equations of Motion, Woods Hole, Massachusetts, 2006.

[15] Jakob C., Konietzky, H.: Partikelmethoden – eine Übersicht, *Technische Universität Bergakademie Freiberg*, Freiberg, 2012.

[16] Höfler, C.: Entwicklung eines Smoothed Particle Hydrodynamics (SPH) Codes zur numerischen Vorhersage des Primärzerfalls an Brennstoffeinspritzdüsen, Dissertation, Karlsruhe Institute of Technology, 2013.

FRP in the Materials Data Space, digitization of material competence as a supplement to Industry 4.0

Dr.-Ing. **R. Schlimper**, Dr.-Ing. **M. Zscheyge**,
Prof. Dr.-Ing. **P. Michel**, Fraunhofer Institute for Microstructure of Materials and Systems IMWS, Halle (Saale)

Abstract

The Materials Data Space provides digital data about materials across all companies along the entire value chain. Networking makes possible shorter development times, production processes with learning capability and new business models, as well as yielding enormous potential for material efficiency, production efficiency and recycling. New materials are the key drivers in the development of innovative products in the manufacturing sector. It is estimated that today up to 70% of all new products are based on new materials. For Industry 4.0 - the close meshing of production with modern information and communication technology – the importance of materials will increase even more. They should make it possible to produce products tailored to individual customer requirements which can be made on demand, adaptively, multi-functionally or by design – doing so cost-effectively, at high quality with short innovation cycles. The Materials Data Space was developed as the basis for material development, production and processing within Industry 4.0. As materials provide the substantive support for workpieces and parts, so is the Materials Data Space the digital image of this. It provides all relevant information about materials in digitized form in an efficient and cross-company digital infrastructure throughout the entire life cycle. Lightweight structures made of fiber composite plastics (FRP) are for reasons of resource efficiency increasingly making inroads into the production of vehicles, machinery and plant. Hand in hand with this, the technological leap from manual FRP production to a semi- or fully-automated production of small to medium quantities has already taken place in a number of locations. For the next step in the direction of large-scale industrial manufacturing to be possible, the corresponding FRP technologies must be made Industry-4.0–capable. The as yet unresolved central problem here is continuous acquisition, structuring, and interpretation of material, process and component data along the entire product life cycle from product creation until the utilization phase. This paper deals with the current status of this

development and the challenges to be tackled in the near future, in particular for the material class of fiber composite plastics. Special emphasis is given here to the needs of the automotive industry. The data platform, which must standardize not only software components but also the hardware aspects, can be divided into these substeps:

1. Integrated acquisition of material, process and component data
2. Fusion and structuring of the measured data for standardized further processing, and
3. Computer-aided interpretation of the data using materials science models.

For FRP lightweight structures produced on the large scale, these variables must be reproduced without omissions across the various scales and life cycles and be made available in an appropriate form to the Industrial Data Space of Industry 4.0.

Two-component air-guide panel manufactured by co-molding and foaming using core-back technology

Dr.-Ing. **A. Roch**, **A. Menrath**,
Fraunhofer Institute for Chemical Technology ICT, Pfinztal;
B. Schmid,
BBP Kunststoffwerk Marbach Baier GmbH, Marbach am Neckar

Abstract

Using the example of an air guide panel for the next generation of BMW 7 series the lightweight potential of foam injection molding in combination with core-back technology of the mold is highlighted. The part is a co-molded, hard-soft combination consisting of two different materials: a polypropylene as the hard and a thermoplastic elastomer as the soft component. First the hard component is gas-laden inside the injection molding barrel and then injected into the cavity. After a short delay time, specific areas of the cavity are opened by core-back technology. Due to this a pressure drop occurs making the material expand in opening direction (→ breathing mold technology). The hard component is subsequently transferred into a second cavity and co-molded with the rubber material along the edge in a single process using only one injection mold. This presentation is introducing the manufacturing process and is focusing on the material savings that can be achieved by the core-back expansion technology which in this case was 20 %.

High-performance polypropylene: does PA 6 still have a future?

Dipl.-Ing. **H. Häberle**, MAN Truck & Bus AG, Munich

Abstract

If at all possible, lightweighting should be cost-neutral in terms of component costs and investment. Better yet, it would be cheaper and therefore allow additional project costs to be evened out in the event of the component entering current series production.

High-performance propylenes (HP-PPs) meet these requirements in a special way, since when swapped out one for one against the corresponding polyamide or polyester blend, the weight of the component falls by approx. 15%. The reduction in material cost associated with this resulting from the lower density is rounded up slightly by a generally lower price per kilogram. Experience shows the volume price to be the decisive reduction variable.

But not only weight and cost efficiency speak in favor of the HP-PPs: reduced CO_2 emissions in all process steps have led us to tackle the replacement of PA6 and pushing forward with this.

1. Introduction

Lightweight construction is an extremely important issue not only for moving masses if requirements such as energy efficiency or fast and precise movements are to be satisfied as perfectly as possible. Even for stationary masses, lightweight construction means among other things lower resource consumption for own production and a lower resource utilization for transportation from A to B.

This circle closes in the case of the truck: on the one hand it must carry lighter in itself, on the other hand, it must be lighter to carry. Both taken together is the efficiency which a CO_2-optimized transport sector requires.

Material lightweighting is often taken today to mean the replacement of metals by suitable plastics since the large difference in density means that correspondingly large reductions in mass can be achieved, provided the plastic satisfies all component requirements. The term then used is the so-called 'metal substitution plastics.'

In the meantime, the so-called high-performance polypropylenes have become a serious competitor for these metal substitution plastics, which normally means the polyamides. Replacing polyamides by HP-PPs in 1:1 substitution generally means a saving of approx.

15% mass. Material utilization costs also fall correspondingly. The HP-PPs are thus pushing at open doors. Given these advantages, implementation on a large scale is only a matter of time.

For the above reasons – CO_2 efficiency, weight efficiency and cost efficiency – we have been working intensively in this area since 2013 and have in the meantime posted some successes in the changeover but also have had to absorb some setbacks. From this we have learnt what needs to be taken into consideration with new developments if the potential of the HP-PPs is to be exploited.

2. Comparison of the properties of HP-PPs and PA-GF60

The components which we wanted to replace in the current bumpers of the Euro 6 series and which are described in the following sections are today still made from PA-GF60 or PBT/PET-GF45. The high-performance PPs had therefore to be measured against the PA-GF60 benchmark – PBT/PET-GF45 is only used in the headlight carrier steel bumper TGS/X and thus 'ran in the slipstream' but was not considered further.

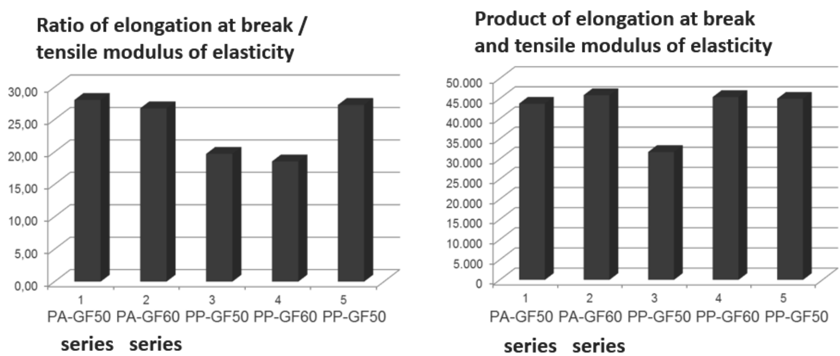


Fig. 1: Comparison of the performance of HP-PP and PA [1]

In the early stages of the project, in addition to the three HP-PPs the PA-GF50, which is used in the foot plate reinforcement of the TGL/M steel bumper, is also compared with the benchmark PA6-GF60. This comparison was made on the basis of 'elongation at break/tensile modulus of elasticity' (Figure 1).

During the subsequent course of the project, more PPs were then included in the comparison (Figure 2). These also included three PP-CF grades with 20, 30 and 40% carbon fiber (12, 13, 14). What is striking about these carbon-fiber PPs is their high stiffness – even their density-related tensile strength is in some cases even higher than the benchmark PA6-GF60. If, however, elongation at break is also included in considerations, the picture changes dramatically.

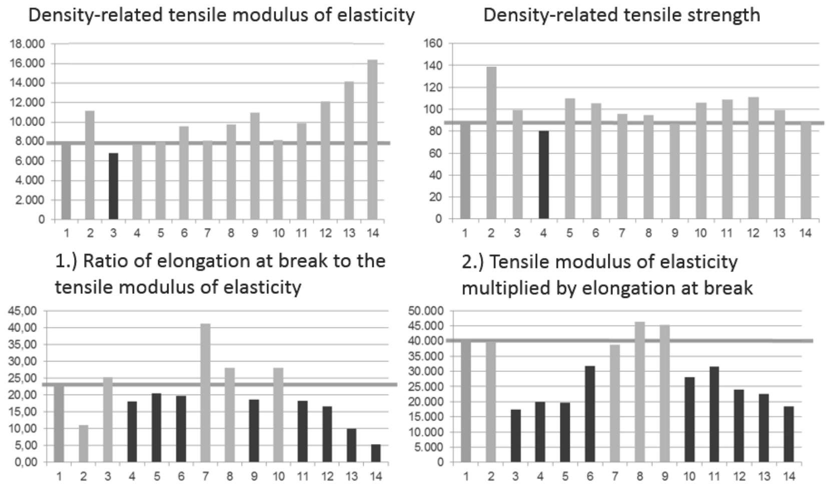


Fig. 2: Number games [2]

These number games show impressively that the comparison of isolated material characteristic values can lead to errors and does not provide useful information. In my experience, with our high dynamic demands a good balance between stiffness and flexibility (elongation at break) is important in the area of the frame components, of which the bumper is one, if the plastic is not to be 'shattered internally' by the high dynamics.

We have, together with our suppliers, examined and evaluated various HP-PPs with different glass-fiber contents as replacements for the PA6-GF60. Possibilities were PP grades with 50% and 60% glass-fiber content. Our suppliers decided in favor of the Rialene grades SGF50 and SGF60 on account of their better flowability, better processability and greater process reliability. Operating-strength tests, both static and dynamic, were carried out on the TGL/M plastic bumper for both HP-PPs. The environmental qualification process according to our internal standard was also completed. This included a heat and coldness test, a static climate test and the automotive industry's well-known alternating climate test.

3. Structural components in the TGL/M plastic bumper

This bumper, shown in Figure 3, was the first of our four bumper types to be tested on the operating-strength test stand. With this bumper we wanted to test both PP-SGFs thoroughly in order to then decide on one of the two for the other bumpers. This bumper was therefore defined as the reference, since it is comparable with the other bumpers as regards the dynamic requirements but its total shot weight of 14 kg represents the heaviest mass of PA-GF60.

This three-piece bumper consists of the left-hand and right-hand headlight areas, the center section with the step. In the case of these three modules, the panels made of non-reinforced PET/PC thermoplastics are attached to the corresponding carrier components. These load-bearing plastic components are made of PA6-GF60 and screwed onto the die-cast aluminum brackets. These in turn are mounted on the steel front-end cross-member.

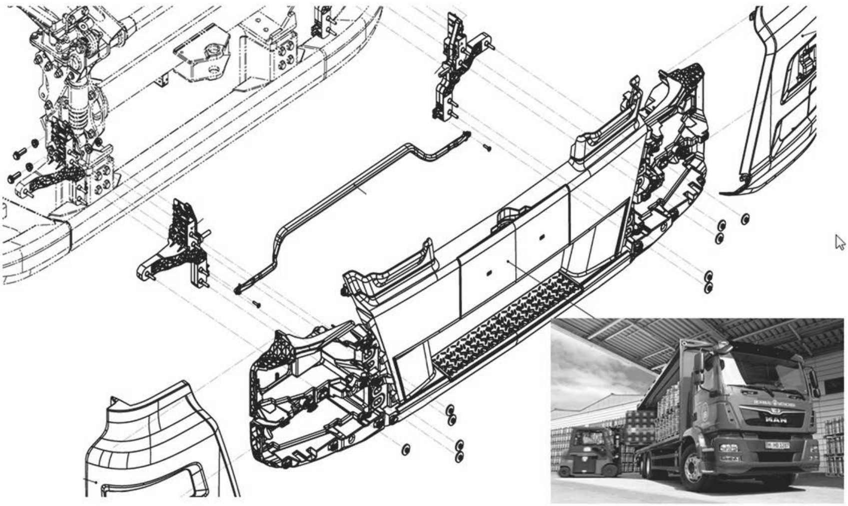


Fig. 3: Three-part TGL/M plastic bumper [3]

While both HP-PPs successfully completed the environmental qualification, they were not successful in vibration testing or the static climb-up test. Wear on the mounting lugs was excessive in the case of the headlamp holders and in the holder middle part the bottom chord did not reach the required tread load of 6 kN.

The static climb-up test simulates the load which can occur when the driver climbs up onto the step to clean the windshield.

In this regard it should be mentioned that the components, since they were matched to polyamide, were not designed in some important details appropriately for PP. Modifying the mold was not regarded as worthwhile on account of the low part numbers involved.
After completion of all tests and the evaluation of results, we decided in favor of PP-SGF50 and did not pursue PP-SGF60 any further.

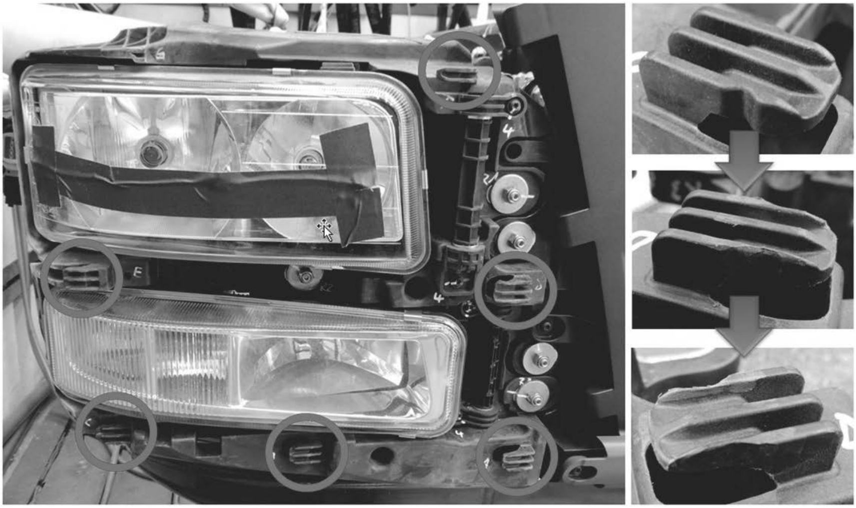


Fig. 4: Wear on the mounting lugs

3.1 Headlight holders

Due to the high dynamic loads with impulses of up to 15G acceleration in all three spatial directions, even with very little play between the components the effect can arise whereby pairs rub against each other, and this can lead to failure of the components. Wear on the mounting lugs was here so great with SGF50 and SGF60 that the every-increasing play between the side panels and the headlight holders resulted in fracture of the side panels. The small image at top right in Figure 4 shows a mounting lug at the start of testing, while two images below it show lugs when the test was stopped. A small amount of wear was also found with PA6-GF60 but this did not represent a problem.
These results show that assemblies must be designed such that components can be installed without any mutual play.

3.2 Beam middle section

With this component the toughest requirement is the tread load of 6 kN (Figure 5). The PPs could here manage only 4 and 4.2 kN, which was quite a way below the 6 kN required — but the difference from the benchmark PA6-GF60 was even greater. Double the value of PP was achieved here. The polypropylenes would therefore have to compensate with somewhat more material and an optimized geometry – with a density advantage of 15% (SGF60) and 23% (SGF50) this should be doable without any excessive loss in lightweighting potential.

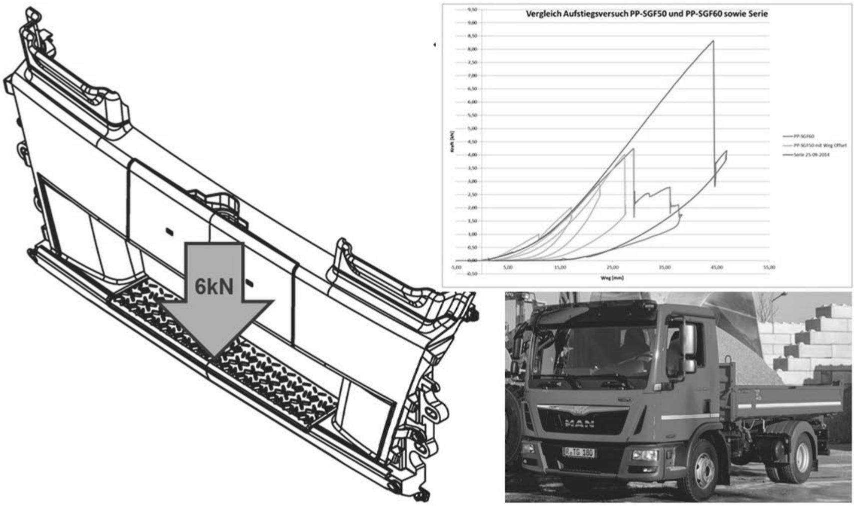


Fig. 5: Breaking stresses of PP-SGF50, PP-SGF60 and PA6-GF60

4. Reinforcement of the foot plate of the TGL/M steel bumper

In the case of the small steel bumper the reinforcement of the foot plate was changed from PA6-GF50 to PP-SGF50. The reinforcement, which is to be seen on the right of Figure 6, carries the PET/PC foot plate. The plate has been given anti-slip pimples to ensure the safety of the driver when he climbs up. In the two cross-sections at the bottom of Figure 6 it can be seen how the reinforcement is incorporated into the lower flange of the steel bumper. The changeover was successfully completed. There were no problems handling the tread load of 6 kN.

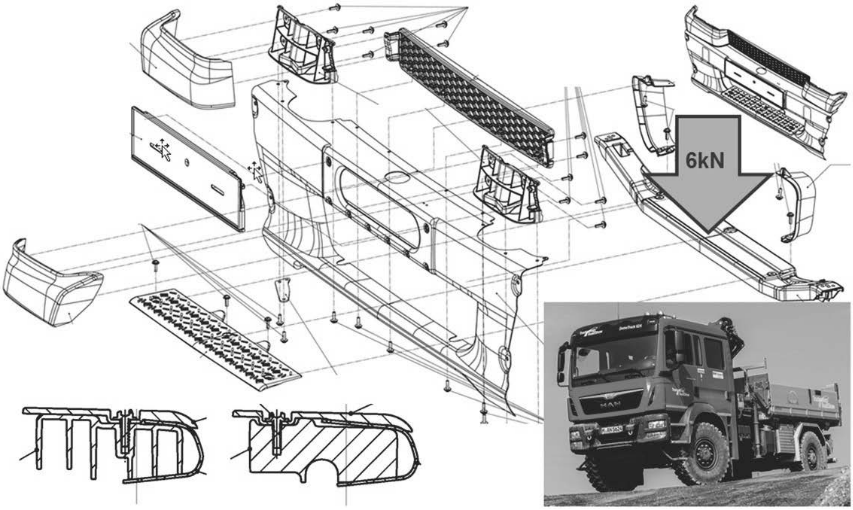


Fig. 6: Reinforcement of the tread plate in the TGL/M steel bumper

5. Headlight holder - TGS/X steel bumper

This steel bumper has been fitted among other things to our heavy-haulage tractor units, which can move up to 250 tonnes gross combination weight.

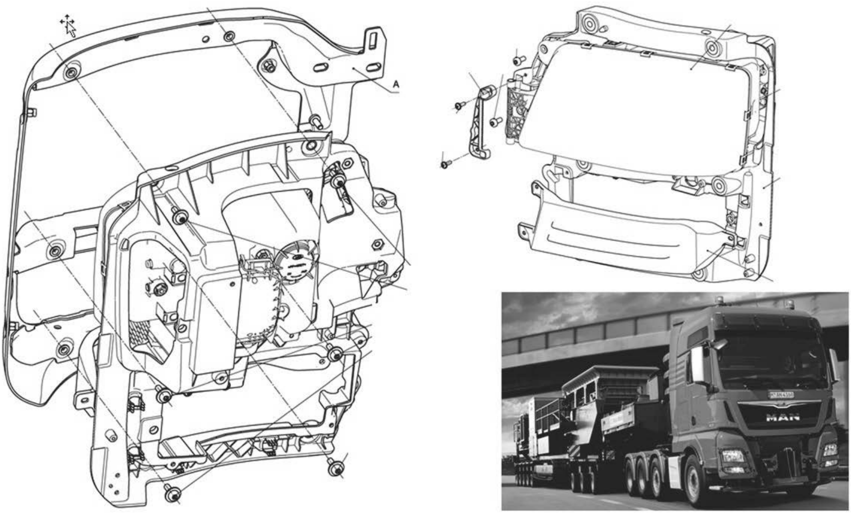


Fig. 7: Headlight holder of TGS/X steel bumper

The headlight holder, which accommodates both the main headlight and the light strip, was made of PBT/PET-GF45 until PP-SGF50 replaced it. Both test runs - operating strength and the environmental qualification - were passed with flying colors.

The light strip is a special item of equipment and includes fog lights, an additional high beam light and the cornering light. Since this is a relevant mass for vibration testing, it is also generally included on the test rigs.

6. Headlight holder - TGS/X plastic bumper

Here too the holders of the main headlight and of the light strip were changed over to PP. The headlight holder is screwed onto the frame front-end in the X direction and is additionally supported in the Z direction via the front underride protector (Figure 8).

Since there was no play in the connection between the side panels and the holder which could have enlarged during the course of testing, no anomalies arose in the dynamic vibration test or the alternating climate test. Production start for these holders in the beginning of 2017.

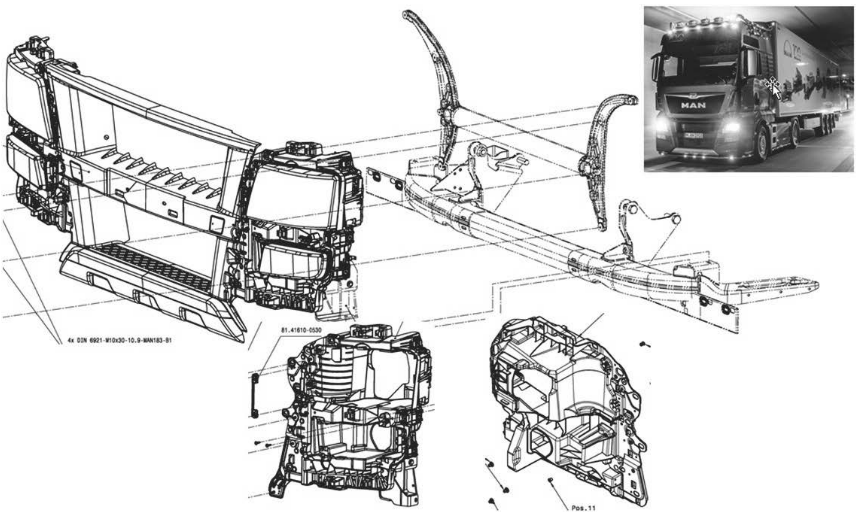


Fig. 8: Headlight holder - TGS/X plastic bumper

7. Summary and outlook

Our examples have shown that the HP-PPs have become a serious competitor to the glass-fiber-reinforced PA6 grades, and have the edge in the most important respects: CO_2, weight and cost. PA6 will find it becoming very difficult to assert itself.

Bibliography

[1] Häberle, H.: Nutzfahrzeugleichtbau durch Einsatz von Kunststoffen, Kunststoffe im Automobilbau, VDI Verlag 2014

[2] Häberle, H.: High-Performance Polypropylene – wird PA 6 noch benötigt? SKF-Fachtagung Polypropylen im Automobilbau, Würzburg, 2016

[3] Häberle, H.: PP-SGF – der Polyamid-Killer? Kunststoff Symposium Süd, Zimmern ob Rottweil, 2016

Electrochemical corrosion and its prevention with polyamides

Dipl.-Ing. **G. Prautzsch**, Dipl.-Ing. **T. Stier**,
Dipl.-Ing. **T. Coeln**, AKRO PLASTIC GmbH Niederzissen

Since 1988 AKRO PLASTIC GmbH as a member of the KD Feddersen Group (Hamburg) has been involved in the production of engineering plastics. Virtually all engineering and even some renewable and compostable materials are processed in-house. The company's own portfolio includes a very large number of polyamide grades. Glass-fiber-reinforced polyamides 6, PA66, 6.10, 6.12 play an indispensable rôle in the international automotive industry today.

Many applications in the automobile are exposed to harsh environmental conditions. Nowadays manufacturers provide very comprehensive warranties for their products. The suitability of all components for a realistically expectable service life therefore plays an ever-increasing rôle. Over the years tests and inspections have become established in the industry which allow prediction of whether components and assemblies will be able to well survive subsequent utilization in the vehicle.

One example of this is the engine test benches in the automotive industry where 3000 hours of continuous running with different load scenarios has long been the norm. Since the 1980s heat exchangers for cooling the engines have been produced with radiator caps made of PA66 GF 30. Many Golf 1 cars can still be seen driving on German roads and also in particular in South Africa – a service life of thirty or more years is verifiable.

In the electrical industry, miniature circuit breakers (MCBs) are produced, and installed in our houses and apartments which last for twenty or more years before possibly being replaced as part of renovation work. Operational reliability must be assured for this long period of time. Even these devices are today basically made of polyamide materials. Other examples include terminal blocks in switchgear cabinets and connector housings in household appliances, these too being in service for more than ten years, even up to twenty years.

All relevant industries have therefore defined test conditions for testing, firstly, the devices, then individual components, and finally the materials. In the home appliance industry a 5000-hour endurance test is common.

An example of a standard emerging from this is the 'SAE/USCAR standard for automotive electrical connector systems'. Here a test cycle with temperatures between -40 °C and 90 °C and air humidities up to 90% relative humidity is applied. An 8-hour cycle is defined, which must be run repeatedly. On the basis of assembly tests of this kind it is determined which requirements will apply to materials so that they will have every prospect of success. One example of this is the GMW3013 Worldwide Engineering Standard which addresses the thermal stabilization of the materials. This cites temperatures of 110 °C for non-reinforced and 140 °C for reinforced polyamides. Materials which meet this standard must still retain 75% of the initial property at the end of 1000 hours testing. Another example is the VW 50127 test specification which concerns PA66 materials for the car passenger compartment. The requirement here is aging at 150 °C for 1000 hours followed by the notched impact toughness test according to ISO 179-1/1eA. The criterion is a decrease of no more than 50% in the material property.

As a consequence of all these demands, the producers of the materials have conducted extensive investigations into aging behavior. New stabilization systems have been developed over the years. Today they make customized formulations possible, at optimal cost, with the best color fidelity and the best service life, depending on the application.

Manufacturers of electrical components in the automotive industry are often faced with the problem of corrosion in live parts. The most common form of corrosion is electrical corrosion, which is found anywhere a liquid electrolyte comes together with two different conductive materials. In most cases these are metals, but even carbon is coming increasingly into consideration. Every conductive material has its own electronegativity. The difference in this value between two conductors is the driving factor for the corrosion process. The 'baser' of the two (that is, the material with the lower electronegativity) here releases electrons to the electrolyte. The result is pitting corrosion, such as can be observed especially in magnesium components installed in a predominantly steel environment. Examples which may still be seen today are the gearboxes of old VW Beetles, many an oil pan and some cylinder head covers from the early 1980s.

In addition, there is also a dry form of electrical corrosion. Lutz Müller of Bosch has described an example of this [1]. ICs (integrated circuits) are components in micro-electronics. They have become steadily smaller and require very fine electrically conductive connections. This is often an extremely thin gold wire ultrasonically welded onto a bonding pad of aluminum. Solutions with an aluminum wire and a gold bonding pad are also possible. In either case an intermetallic phase (IMP) forms in the welding area. This intermetallic phase has a particular sensitivity to corrosive processes. In components which failed in trials, their longitudinal section was examined under the scanning electron microscope. It can be very clearly demonstrated that the IMP has disappeared. Analytical investigations of corroded contacts have shown that iodine, bromine and potassium which do not originate in the contact materials are evidently involved in the corrosion process. It was possible to identify these elements as ingredients in the formulations of the polyamide materials. Housings for controllers or connectors used in the automotive industry are often made from PA because PA easily satisfies all known constraints. Polyesters are sometimes at the limit of their capabilities when tested under hot and humid conditions (85 °C and 85% relative humidity for 1000 hours).

Besides failures due to corroded-away material, failures occur from time to time resulting from a coating building up on a contact which increases constantly in size and finally causes a short circuit between adjacent contacts. These coatings could be attributed to the metal soaps (potassium stearate, aluminum stearate) also frequently used in PA formulations.

Some of the automotive developers and system suppliers have sought new solutions for this problem which permanently prevent not only corrosion but also the formation of coatings. Work has already started in this area at AKRO PLASTIC as well. Here the first and simplest step was to create formulations which did not use the problematic elements.

Iodine-induced corrosion from the gas phase proved to be a very difficult problem.

Very small concentrations of iodine in the material were identified as corrosive. Since iodine already sublimates at moderately elevated temperatures, corrosion even occurred in components at a distance of 10 cm from PA containing iodine. Consequently AKRO PLASTIC decided to try for a limit value of 1 ppm for the problematic elements of iodine and bromine. It should be able to guarantee this limit value for every batch produced. This therefore calls for a measuring method which correspondingly tests the raw materials and the finished compound. At the time when work started no such method was available on the market. Analysis in the field of metallurgy has for many years now used X-ray fluorescence with an accuracy of about 1 ppm. As regards use with polymers, no equipment supplier was ready to affirm this figure.

It was therefore necessary for AKRO PLASTIC to succeed in developing a method which could be sufficiently precisely calibrated. Success was achieved after about a year of intensive work. The devices in use today can quantitatively determine most elements of the periodic table with a reproducibility of 0.1 ppm to 2 ppm. (Elements up to atomic number 11 (sodium) cannot be measured). This means that AKRO PLASTIC has made the crucial step forward. In the production of 'electrically neutral' (EN) polyamide compounds, experience can now be increasingly gathered as to which constraints must be observed in order to prevent accidental inclusion of iodine or bromine. Chlorine was in most cases not regarded as a critical element. It is also difficult to maintain a total absence of chlorine when cooling water is drawn from the public network. Sampling often leads to contamination of the samples with

chlorine from skin contact. In a separated system which was deliberately filled and operated with pure water, it has also become possible to produce a product which demonstrably contains less than 1 ppm chlorine.
The conditions are thus met for electrical and electronic assemblies being able in future to operate in the long term under difficult climatic conditions. EN polyamides are available as materials for housings and connectors.

References

SAE/USCAR standard
GM Worldwide Engineering Standard 3013
VW Group standard 50127
Korrosion von Metallen durch Temperaturstabilisatoren und Flammschutzmittel in Polyamid, Lutz Müller et. al. ; Reutlingen; paper presented at SKZ in June 2016.
Plant pictures Leopold Kostal GmbH
Plant pictures AKRO PLASTIC GmbH

Application of organo-sheets in underbody components: cost- and weight-optimized off-road package

Dipl.-Ing. (FH) **R. Apfelbeck**, **S. Müller**, B.Eng. (BA),
AUDI AG, Neckarsulm

Abstract

Audi stands for Vorsprung durch Technik. True to this brand claim Audi is continuously developing the most advanced technology. Appropriately enough for a sporty brand profile Audi's models have a distinctive face and sporty lines. The claim of 'high-tech in premium cars' also continues in well-thought-out component solutions. One example of this is the newly developed damping pan which is used by platform users with off-road packages. This component relies on an intelligent mix of materials.

Fig. 1: The new Audi Q7 – comfort at the highest level

This technical article describes the successful use of organo-sheets in the underbody area and the advantage of using low-weight reinforcement thermoplastic (LWRT). It concerns an all-group platform project in the SUV segment which with the first entry into service of the new Q7 satisfies the technical and economic requirements of all users of the platform.

1. Structure and function of an underfloor panel

In vehicle development the material polypropylene (PP) has become established in the underbody area. How this material is processed and how it is used should be distinguished. In compact class cars, polypropylene (PP) is used in reinforced and unreinforced forms.

For mid-range cars the materials are processed in a modified form. Here glass-reinforced polypropylene (PP) is used in the compression-molding pressing process and is referred to as glass-mat-filled thermoplastic (GMT). Low-weight reinforcement thermoplastic materials (LWRT) are used in premium cars and offer optimum properties as far as lightweight construction and acoustics are concerned. Different grades of these material types are available on the market.

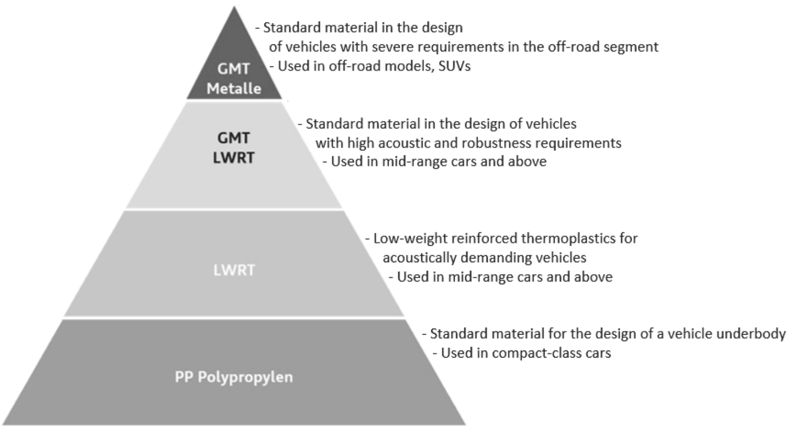


Fig. 2: Use of materials according to requirements and vehicle class

Product specification requirements were clearly defined in the development of the new Audi Q7, the Porsche Cayenne, the VW Touareg and the Bentley Bentayga. This meant that development work could be carried out with clear targets at a very early stage.

The development departments were successful in satisfying the strict requirements in the areas of all-terrain package, curb descent, connection to the front end, the acoustic efficiency of the component and also in taking into account different roadway conditions.

2. Structure of a vehicle underbody

The front –also the most demanding area – is equipped with the most diverse materials in the underbody panels, depending on the product specification requirements as regards acoustics, vehicle architecture, technical performance and the aggregate structure of the vehicle. Usually the damping pans of the vehicles are designed on the basis of PP-EPDM (poorer acoustic performance than LWRT, but cheaper) or LWRT (increased acoustic performance). In the case of high demands regarding all-terrain robustness, GMT or metal is used.

With high acoustic requirements, the vehicle mid-section can be designed with extensive areas of LWRT. If acoustic performance requirements are less demanding, PP-based materials such as D-LFT, PP-EPDM, SMC or PP-GF can be used. Materials such as GMT or metals are used for vehicles in the SUV segment which must have a high abrasive resistance to gravel and chippings.

The rear section of the vehicle is normally fitted with panels to protect the fuel tank, major assemblies or the chassis. Various start-up elements contribute to optimized aerodynamics. The acoustics of the front and rear ends play a major rôle in current and future projects.

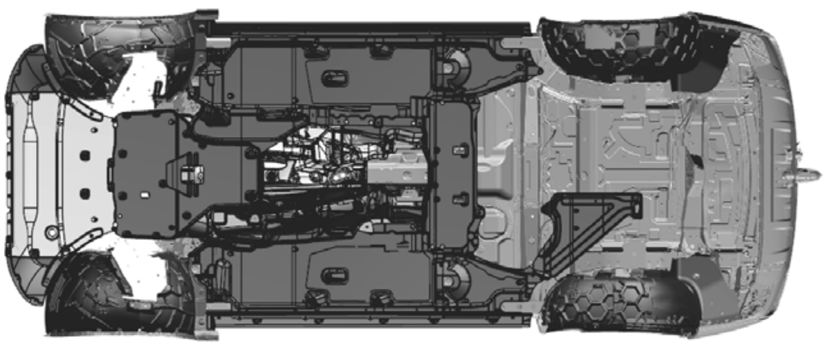


Fig. 3: Structure of a vehicle underbody in the Q7

3. Requirements for bad-road countries

All of the platform vehicles are sold worldwide and therefore must be optimally designed for the corresponding roadway conditions in each case. In countries with poor roads it is possible for vehicles to bottom out and for the underbody to come into contact with the roadway. This means that these stresses must be absorbed such that damage to the powertrain and radiator assembly can be ruled out. The underbody panel is eminently suitable for absorbing these load peaks by sliding.

Vehicles which must meet the requirements profile of a bad-road country are fitted with metal or GMT-based damping pans or lateral mid-vehicle shields. Hydrodynamic interaction when driving into or out of pools of water combined with high stresses from gravel and chippings leads to fatigue in a base material such as LWRT, for example. To find a material fit for trials and ready for series production, a material was required which was more resistant than a basic LWRT, more impact-resistant than GMT and, with regard to increasingly strict legal requirements, lighter than metal.

4. Solutions for bad-road countries

Twenty years of experience in lightweight construction go into the development of the new Audi Q7. We selected LWRT and organo-sheet to achieve an intelligent solution with the simultaneous substitution of metals in the underbody segment.

To prevent repeated contact of the damping pan and lateral underbody panels with the roadway leading to failure of the material, in the bad-road variant the entire surface of the components was designed with an organo-sheet. The lateral panels were implemented with a newly developed special type of organo-sheet.

5. Structure of organo-sheets

An organo-sheet is a fiber composite made of glass fibers, carbon or aramid, and also a polymer matrix, such as polypropylene. This material is characterized by its high rigidity and strength, and is therefore ideal for use in lightweight applications.

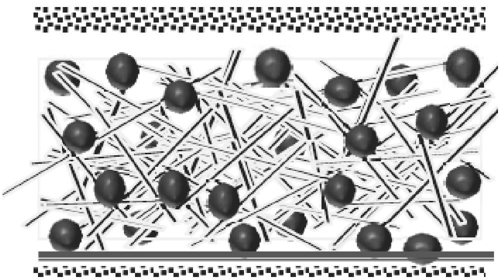


Figure 4: Structure of an underbody for bad-road countries

This special material structure can be produced in a one-step process and does not require additional process steps. A height of 15-20 mm can be achieved by lofting (expansion of the material by heat input). This leads to an increase in the areal moment of inertia, in rigidity and in acoustic performance.

5. Production of organo-sheet LWRT underbodies as regards process engineering

Flat components with low levels of deformation are very suitable for this kind of production. The background to this is the different shrinkage properties of an LWRT and an organo-sheet, such as Tepex, manufactured by the Bond Laminates company. Due to the difference in weight per unit area, excessive sudden increases in height will, despite PP-GF as the same base material, lead to the component deforming.

Consequently a decision must be made, depending on the component geometry, as to what form the manufacturing process must take. Here there are several possibilities for connecting the organo-sheet to the LWRT. Simple and flat components can be produced with semi-finished products by laminating an organo-sheet onto LWRT. With more complex components and large differences in weight per unit area, the two semi-finished products should be heated separately. The reason for this is the different energy input into the material. The sheets are then inserted into the compression tool and the compression and stamping operations then follow.

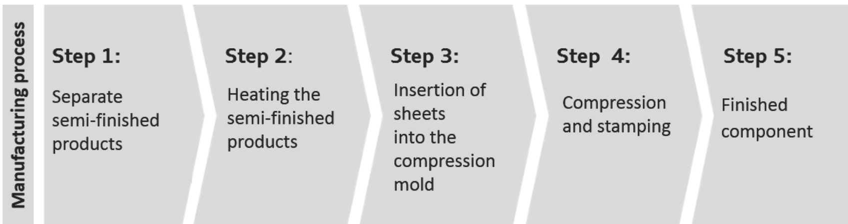


Fig. 5: Production of an LWRT/organo-sheet composite

6. Benefits of using organo-sheets

Weight

The new Q7 is a car with a very good height-to-width ratio: 5.05 meters long, 2.99 meters wheelbase, 1.97 meters wide and 1.74 meters high. In the version with the 3.0 TDI engine the new Q7 measures only 1995 kg on the scales (curb weight without driver in the case of a Q7 with five seats) which is 325 kg less weight than the predecessor model – as much as a grand piano.

A contribution to this weight saving is made by the developments in the underbody area resulting in the elimination of metal and GMT. The use of organo-sheet in the underbody has made it possible to save a total of 7 kg in the bad-road package.

Aeroacoustics

The robust yet elegant appearance of the Audi Q7 is enhanced by the high-grade acoustic components. The Audi Q7 is best-in-class with its aeroacoustics. The drag coefficient of this large SUV is 0.32 – thanks to elaborate technical solutions, a top result in the segment. A significant contribution is made by the design of the underfloor area, running from the vehicle front-end to the rear.

One major advantage the LWRT/organo-sheet structure has over a metal or GMT is its higher acoustic performance. Figure 6 shows the difference between a GMT and an LWRT/organo-sheet composite. Even in the low frequency range, the delta clearly stands out and runs virtually unchanged into the high-frequency range.

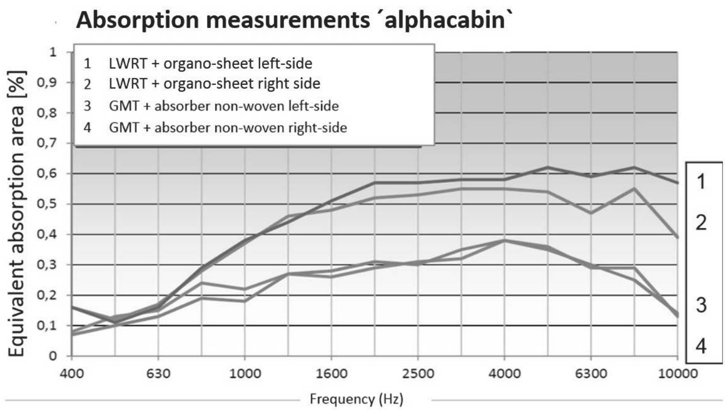


Fig. 6: Absorption measurement of geometrically identical underfloor components, different materials

Robustness

Fig. 7: Bentley Bentayga in off-road testing

The premium cars developed in this platform project stand for performance and exclusivity in the SUV segment. The Bentley Bentayga based on this platform is a benchmark for the unification of opulent appointments and comfort under the toughest conditions.

The use of organo-sheet has resulted in all points of the product specification requirements in the SUV segment being satisfied.

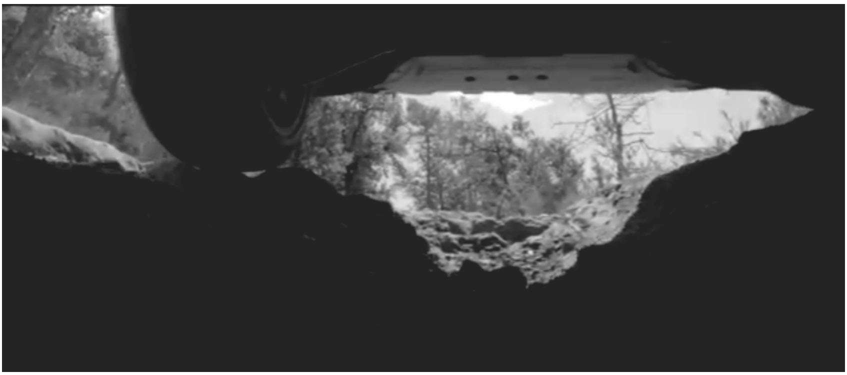


Fig. 8: Testing the underbody on the off-road test track

In the event of an impact-like stress, such as occurs for example when a vehicle bottoms out descending a curb or with a high level of gravel impacts, the LWRT/organo-sheet composite can absorb a large proportion of the energy by elastic deformation. This is a great advantage over a GMT material, which fails earlier due to its lower impact resistance.

Costs

In addition to technical requirements, the development of a component requires costs to be taken into consideration. In addition to item costs, legal requirements can mean additional costs when stipulated values for CO_2 are exceeded. Since emissions are directly related to weight, there is a very strong motivation to keep weight down by using the optimum material.

By substitution for the metal underbody shield and also the GMT-based side panels, Audi has succeeded in reducing costs by one half.

7. Conclusion

With the second generation of the Audi Q7, vehicles using this platform are setting new standards in their market segment: powertrain, chassis, lightweight construction, driver assistance systems convince with innovative technology. The new Audi Q7 is up to 325 kg lighter than its predecessor and saves up to 50 grams of CO_2 per kilometer.

The damping pans and underfloor components for bad-road countries are well-thought-out products created in the successful collaboration of Audi's development department and Audi's partners and group colleagues.

This development impressively demonstrates that a purpose-designed composite of the most modern material opens up new innovative solutions for lightweighting. Challenging requirements and demanding tasks in the areas of bad-road country design, acoustics, structure and lightweight construction have been met in an extremely high-quality final product for the customer.

Innovative plastics in automotive engineering will play an even greater rôle in the future since they facilitate improvements in the design of lightweight construction. Different production methods in combination allow a high degree of design freedom and also offer the potential to meet future legal requirements.

Fig. 9: The Audi Q7: the new begins where limits end

The result of using an ultra-lightweight acoustically high-grade material in conjunction with an organo-material, as compared with a metal, is for Audi and ultimately for its customers reflected in the aspects of efficiency, fuel consumption and comfort by optimized acoustics. With its technical implementation, Audi has succeeded, and will succeed in future projects, in being well-positioned in the SUV segment, as expressed in the slogan 'Vorsprung durch Technik'.

Explanations of terms

Organo-sheet = material fiber composite consisting of continuous strand fibers and a polymer

LWRT = Low-Weight Reinforced Thermoplastic

Lofting = produced in LWRT chambers which are acoustically effective and where the component thickness can also be simultaneously increased

Consolidate = LWRT in the pressed state

AU536 = Audi's internal designation for the Q7

B9 = Audi's internal designation for the A4/A5

D-LFT = continuous strand-reinforced thermoplastic

PP-EPDM = thermoplastic

SMC = Sheet Molding Compound – fiber matrix with fiber reinforcement

PP-GF + polypropylene + glass fiber

Sources

[1] VDI Wissensforum GmbH: Kunststoffe im Automobilbau, Düsseldorf, 2011

[2] AUDI AG, product information, 2014

Interior concepts: vehicle interior design developments relevant to the future

J. Friedrich, Car Men GmbH, Idstein

- Overview of current design-related cockpit developments: deformation, transformation, information
- Impact of 'autonomous driving' on the cockpit design
- Definition of interior design factors for 'autonomous driving' as a function of the driver/passenger and vehicle infrastructure
- Outlook regarding the growing 'disappearance tendencies' in the cockpit

Overview of current design-related cockpit developments

The factors of deformation, transformation and information make for new interior concepts and are explained by examples from the last global auto fairs.

Current and future changes are closely linked with the choice of the drive unit: conventional and/or electric. These affect the dimensions and the configuration of the vehicle interior.

The individual design preferences of the various social environments and nationalities play an equally important rôle as the technological basis of the interior. Our studies over the last 15 years have shown that in perceived quality analyses accurately meeting the individual design taste of the end customer heavily influences his impression of quality.

Impact of 'autonomous driving' on the cockpit design

Direct impact on the vehicle:

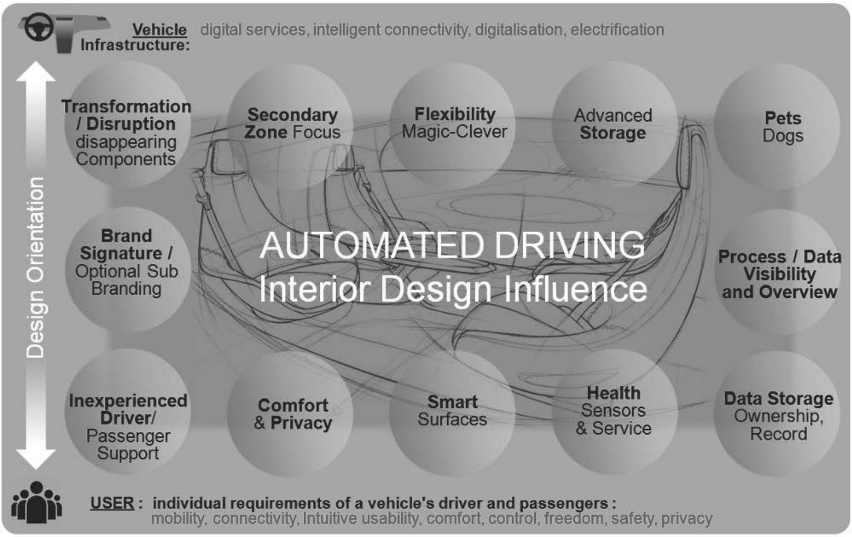
- Enhancement of the interior: digital surfaces plus authentic materials
- Variable/flexible components such as steering wheel, seats, center console, and so on
- Automatic configuration of the interiors to suit the individual user profile
- Expanded utilization situations: for example, health sensors, delivery service for data storage, use / information and dissemination

Taking into account the different levels / development stages in autonomous driving, a dedicated roadmap is created for each interior component.

Definition of interior design factors for 'autonomous driving'

The question often arises as to what effects autonomous driving has on the vehicle interior. We have tried to create an overview.

Each of these factors can be individually turned up or down for the individual vehicle components. This yields a component profile of design-related interior factors in the case of autonomous vehicles, depending on the needs of the driver/passenger and on the vehicle infrastructure.



Outlook regarding the growing 'disappearance tendencies' in the cockpit

Due to the ongoing paradigm shift from analog technology to digital mechanisms, components are increasingly changing.

These changes in interior components, which occur during different stages of development, are examined through the example of the situation of center consoles.

Thanks to the increased use of automatic transmissions, significant changes and material savings can be observed in the design of the center console. The design picks up on the idea of the 'lightweight look'.

To sum up, three stages of development can be implemented in center consoles:

- The first step in the direction of the 'modern interior' is an apparently floating center console
- The second step is the integration of the center console into other components, such as the seat
- The final step is the disappearance of the center console.

Lightweight design for increased payload: new ways using polymer composites and physical foaming

L. Jerpdal, M.Sc. M.E., Dipl.-Ing **J. Hain**, Dr.-Ing. Dipl.-phys. **O. Täger,**
Volkswagen Konzernforschung, Wolfsburg

- Self-reinforced poly(ethylene terephthalate) (SrPET) organo-sheets for lightweight design
- Overmolding of organo-sheets using physical foaming
- In-mold coating (IMC) on organo-sheets for class-A surface finish
- Technology for heavy truck exterior body panels

Composite organo-sheets are commonly based on endless glass- or carbon-fibrereinforcements and polymer matrices. A novel group of composite organo-sheets are self-reinforced polymer composites (SrPC), which are materials based on a thermoplastic reinforcement and matrix of the same polymer type as the reinforcement, that is, both poly(ethylene terephthalate) (PET). SrPC materials are ductile, have low density and good recycling properties. Organo-sheets show a limited degree of design freedom but overmolding can be used as technique to overcome this disadvantage and to efficiently increase function integration. Several concept parts from organo-sheets overmolded with glass-reinforced composite material have been shown in the past. When a reinforced material is used for overmolding not only is mechanical performance increased but also dimensional stability is improved, which is good result since warpage is a challenge due to the volumetric shrinkage of the overmolded material. Reinforced materials used for overmolding have higher density compared to unfilled material but are well suited for physical foaming due to the fact that the reinforcement acts as nucleation for foaming. Applying physical foaming for overmolding can not only save weight but can also reduce warpage caused by volumetric shrinkage because the pressurized gas counteracts the material shrinkage effect and lowers the internal stresses. The woven fibre structure in an organo-sheet influences the surface finish thereby making it very difficult to achieve a class-A surface finish. However, for a part that is overmolded by injection molding there are possibilities of using in-mold coating (IMC) in sequence with overmolding to create a surface with a class-A finish. This presentation shows a concept with self-reinforced poly(ethylene terephthalate) (SRPET) using a new technology for physical foaming, called IQ foam, for overmolding and in mold coating in sequence, as a technology for the efficient manufacturing of lightweight parts with high-quality surface finish. This concept has been evaluated for the use in exterior body panels for heavy trucks.

Lightweighting with carbon: lighter and cheaper than steel

Holistic consideration of the lightweighting potential and process costs of CFRP

Dipl. Wiss.-Ing. **G. Kalkoffen**, CarbonTT, Stade

Abstract

Lightweight construction using carbon-fiber-reinforced plastic (CFRP) is fairly well-known in high-priced applications. If there are however certain degrees of freedom such that material properties and manufacturing parameters can be taken into consideration, CFRP components can then deliver advantages not only in weight but also in process costs.

1. Lightweighting potential of CFRP

The strength (tensile, compressive) and buckling resistance of CFRP is about six times higher than steel, while the modulus of elasticity is 40-70% lower. Larger cross-sections than are the case with steel are preferred in order to compensate for the lower moment of inertia of CFRP. Installation spaces permitting, a mass reduction of 40-70% is possible.

2. Consideration of CFRP process costs

One kilogram of carbon fiber costs 10-15 times more than high-tensile steel. Depending on quantity, complexity and demand, there is a wide spread of the resulting component manufacturing costs - for both materials. If it is possible to decouple an entire module for which a process suitable for fiber can be used, this will result in cost advantages with regard to corrosion protection (electrophoretic coating in particular) and assembly processes. This is not possible without a comprehensive parametrization of all CFRP components in the design phase so that material and process costs can be optimized just like weight and strength. The particular weighting given to the parameters should be consistent with the customer value of reduction in mass.

Development of a carbon-composite electro-transmission housing

Dipl.-Ing. (FH) **M. Kreutzmann**, Dr. **T. Schneider**,
Dipl.-Ing. **R. Rademacher**, P+Z Engineering GmbH, Munich

Abstract

If electrically powered vehicles are to have a long range, their lowest possible weight is of crucial importance. For this reason, components in the drivetrain, such as the two-stage transmission typical of electric drives, must offer an optimal weight while meeting all requirements. The weight of this transmission can be reduced by substituting materials of a lower specific weight for the existing housing materials.

A very interesting possible material here with regard to its mechanical properties is a carbon-fiber-reinforced thermoplastic matrix in combination with the possibilities established in production. The most challenging demand made of this combination of materials in a transmission housing is compliance with the rigidity values required, even at operating temperatures above 100 °C. These have a significant impact on the service life and acoustics of the transmission and therefore decisively determine the geometric design.

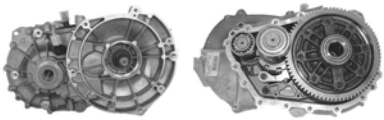
In this project, the aluminum housing of a conventional electric transmission was replaced by a housing made of fiber-reinforced thermoplastic. The basic approach to satisfying all of the requirements made of the transmission housing provides for using an organo-sheet (thermoplastic) which is overmolded with a short-fiber-reinforced plastic. A significant reduction in shaft tilting is made possible by using aluminum inserts which can transfer to the organo-sheet the loads introduced in the bearings. Rigidity targets can be achieved with the aid of additional injection-molded ribs and UD tapes.

In the development phase, the various concepts are examined morphologically with the aid of FE analyses and their feasibility assessed. Whether the concepts can be produced or not is assessed in compression- and injection-molding simulations, and optimizations carried out as necessary. The load paths of the housing are determined with the aid of topology optimizations, taking tension and compression ranges into account. The constructive design so derived serves as a geometric starting point for optimizing the layers of the organo-sheet, and optimization of the UD tapes and injection-molded ribs.

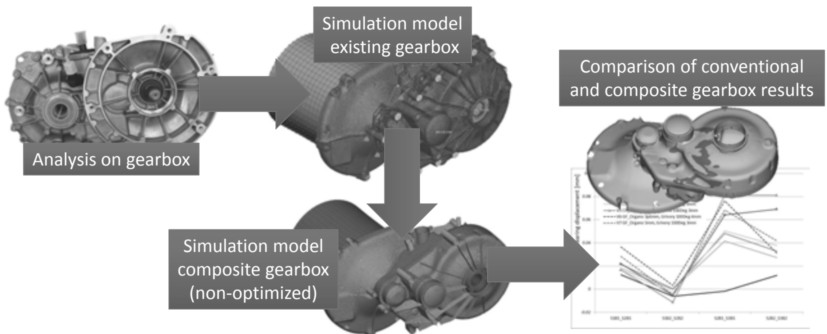
Tool production, which is tightly bound into the development process, secures producibility, with the first prototypes of a housing half being manufactured in a two-step process. In the first step, the organo-sheet and the reinforcing UD tapes are heated and then shaped within a compression process. The outer contour is then created by water-jet cutting. In the second step, the organo-sheet is heated again and then overmolded in order to create the ribbing geometry and thus the final shape.

MOTIVATION

- Development and manufacturing of composite parts with a thermoplastic matrix
- Produce a working demonstrator with an overmolded organo sheet based on an series used part with a conventional material concept (e.g. aluminum)
- Keep manufacturing costs of existing part (as close as possible)



PHASE 1 – GENERAL FEASIBILITY



- Reengineering of an existing aluminum gearbox → determination of target values
- Estimation of general feasibility with composite housing

✓Feasibility confirmed

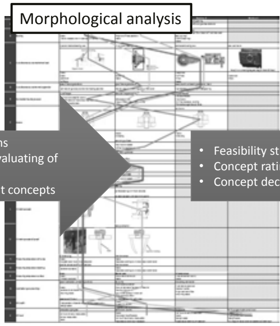
1ST CONCEPT

Functional specification

Category	Description	Value/Info
Geometry	Dimensions	Design space
	Tolerances bearing positions	Bearing positions ± 20µm
	Tolerances flange mounting surfaces	CAD
	Mass without interior parts	less than 5,826kg
Loads	Input torque	130 Nm at 4000 min^{-1}
	Crash loads	10g for x,y,z
	Impact loads	Mounting, stone chip
	Thermal heating	100 °C
Functional	Power transmission	According t
	Torque support	Mounting g
	Deflection bearings due to loads defined	According t
	Acoustics	According t
	Disassembly	Housing an
	Oil proof	Flanges sea
	Oil level	Measuring defined oil level
Environmental	Temperature	-30 to 100°C
	Corrosion	Contact corrosion
	Fluid resistance	Transmission oil
	Fluid resistance	Engine oil, petrol, rim cleaner, antifreeze, brake cleaner, aceton, brake fluid, batterie acid, cooling fluid, wash chemicals
Costs	Manufacturing	According to smart gearbox costs
Maintenance	Oil drain plug	
	Air drain petcock	ensure compansation overpressure, avoid oil loss
	Oil refill plug	Seperate or combined with air drain petcock
	Measuring temperature	Oilsump, bearings, gearbox surface

- Deriving functions
- Searching and evaluating of several solutions
- Creating different concepts

Morphological analysis



- Feasibility study
- Concept rating
- Concept decision

Concept evaluation

Further investigation only for appropriate concepts

Concept 1 | Concept 3

1ST CONCEPT

Concept decision

FE-Analysis Basic

- Deriving Composite FE-Model for feasibility analysis

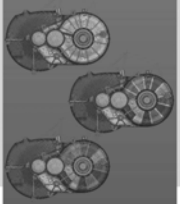
- FE-Analysis

Movie

- Deriving counter measurements (ribs,UD)

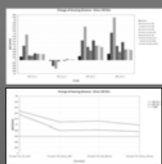
Deriving Variants

- Considering Basic simulation results



...

Stiffness evaluation



- Comparing with stiffness target (reference housing)

Concept desicion

- Concept 3 with CF organo sheet feasible
- Concept 3 with GF organo sheet probably feasible
- Concept 1 not feasible

PHASE 2 – 1ST DRAFT

1st concept

- Functional specification
- Function list
- Searching for solutions
- Creating different concepts
- Economical and technical evaluation
- Concept decision

1st draft

- Design 1st draft (design space)
- Topology optimization for load path and divisional plane
- Design revised draft
- Reduced FE-model and layer optimization
- Economical and technical evaluation
- Material decision
- Detailed draft and evaluation
- Approval detailed draft

Detailed design

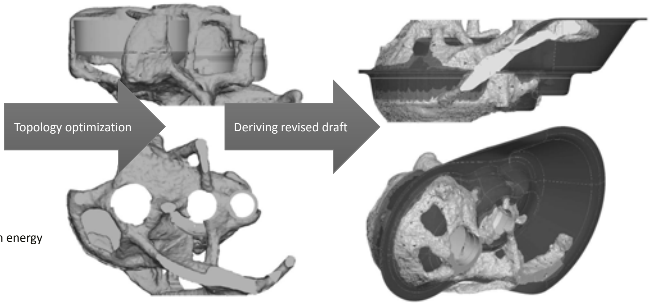
- Creating detailed design
- Approval design
- Creating design documents
- Approval manufacturing documents

1ST DRAFT

Topology optimization

Optimization process | **Optimization results** | **Deriving shape**

Movie



Setup

- Minimization of strain energy
- Mass constraint
- Stiffness constraints
- Strength constraints

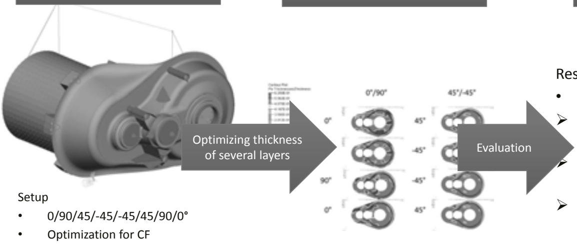
1ST DRAFT

Layer optimization

Shell model for layer optimization

Optimization result

Derived results



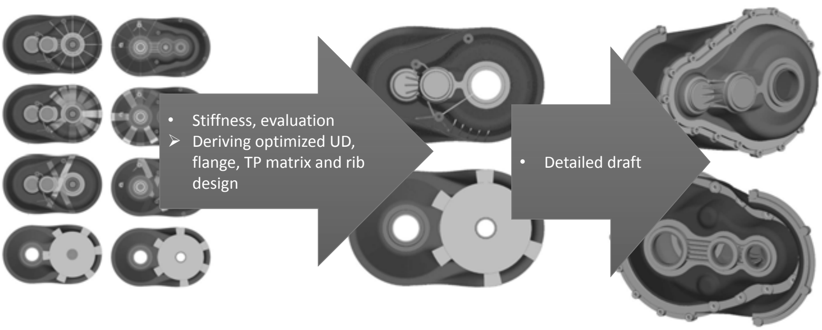
Setup
- 0/90/45/-45/-45/45/90/0°
- Optimization for CF
- Laminate thickness 0.6 to 6 mm
- Balanced 45°/-45° plys
- Considering stiffness results

Results
- Higher thickness for 45°/-45° plys
  - ➢ Using especially 45°/-45° plys to further improve stiffness
  - ➢ Reduction of laminate thickness by mainly using 45° plys
  - ➢ Further local reinforcement measurements by using UD-Tapes

1ST DRAFT

Further stiffness optimization

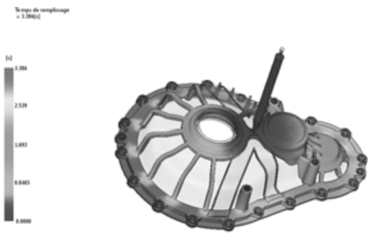
Deriving variants based on FE-Optimizations



1ST DRAFT

Feasibility analyses of manufacturing

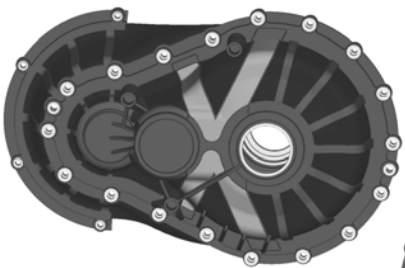
Injection molding simulation



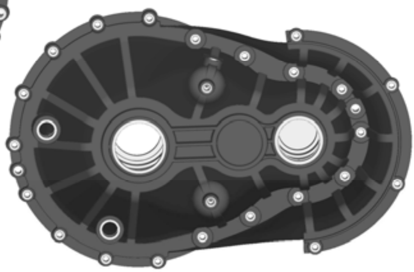
Stamping simulation

Movie

DETAILED DESIGN

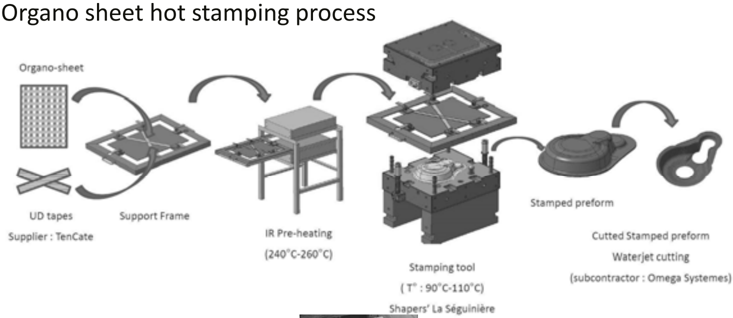


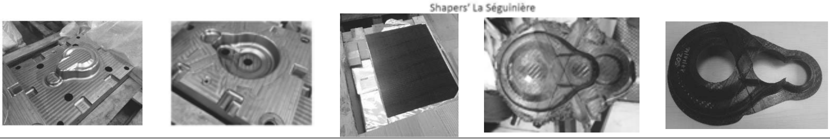
- Detailed design with CF organo sheet
- GF reinforced TP injection molding material
- Aluminum inserts for bearing position
- Metal inserts for screws



MANUFACTURING

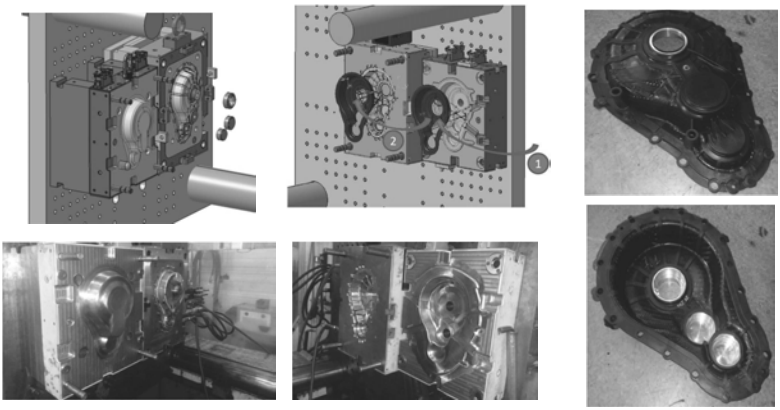
Organo sheet hot stamping process





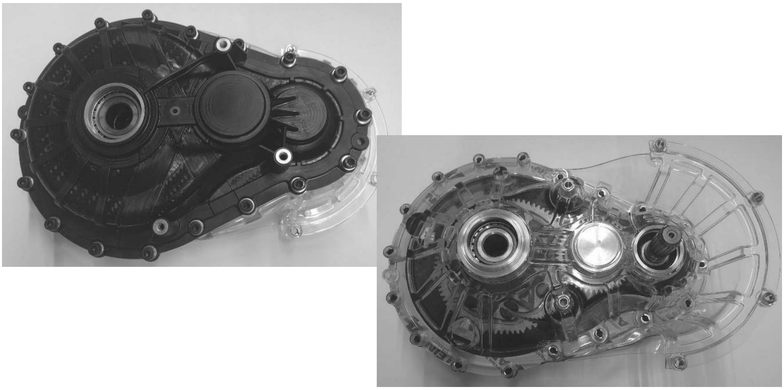
MANUFACTURING

Overmolding process



DEMONSTRATOR

Assembly



FURTHER STEPS

- First test of prototype cover to validate FE simulations
- Validation of stamping simulation results
- Mapping of stamping results to consider in FE simulations
- Manufacturing 2nd part of gearbox
- Testing with complete gearbox assembly

The use of an alternative material for engine encapsulation for Trucks

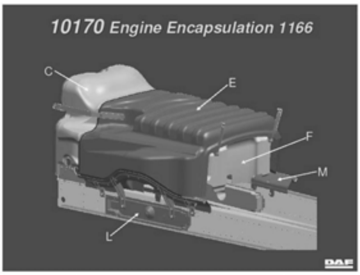
T. van den Einden, DAF Trucks,Eindhoven,The Netherlands;
Dipl.-Ing. **K. Menke**, Johann Borgers GmbH & Co., Bocholt

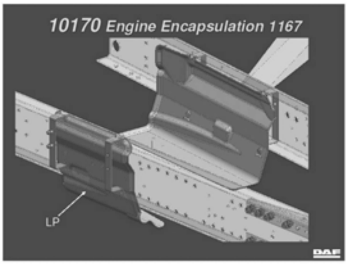
Introduction

- Short introduction DAF Trucks Engine encapsulation
  - Specifications
  - Target on weight
  - Target on costs
- Material survey
- Triflex mineral
- Summary

Introduction Euro 6 Engine Encapsulation

Engine Encapsulation





Specifications

The purpose of the Noise Encapsulation is:

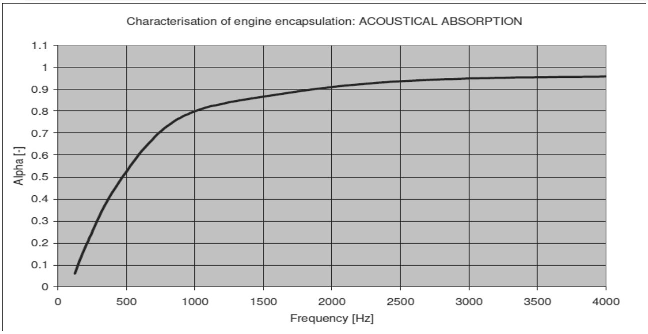
- Reduction of interior noise in such a way that requirements for interior noise are met.
- Reduction of exterior noise in such a way that legal requirements for exterior noise are met.
- Thermal insulation between engine compartment and components outside the engine compartment.
- Guidance of cooling air flow in such a way that recirculation is minimized and cooling performance optimized.

Specifications

Main points for the specification are:

- Temperature range between -40 and 120°C
- Vibration range
- Stone chip resistance
- Steam cleaning
- Thermal isolation
- Noise absorption and isolation
- Flame ability V0
- Air flow resistance
- Legal requirement on used materials
- Lifetime at least 8 years or 1.600.00 km

Targets



Targets

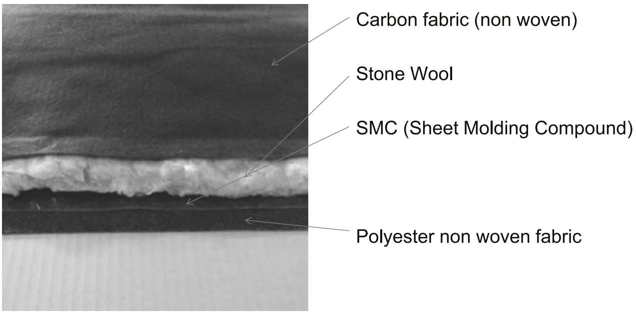
- Weight reduction of 25% with the same acoustic behaviour
- Cost reduction of >10% compared with the current material

Material survey

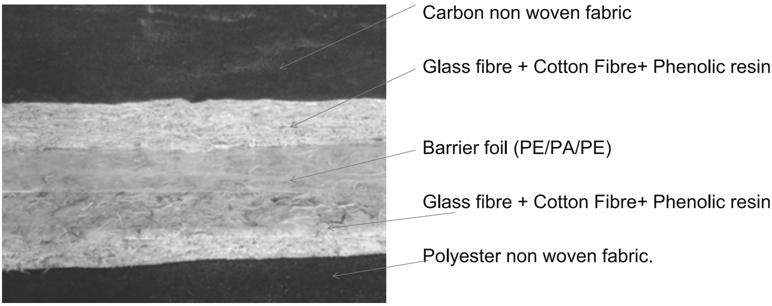
- SMC in combination with an absorber

- Cotton fibres with phenolic resin in combination with glass fibres.

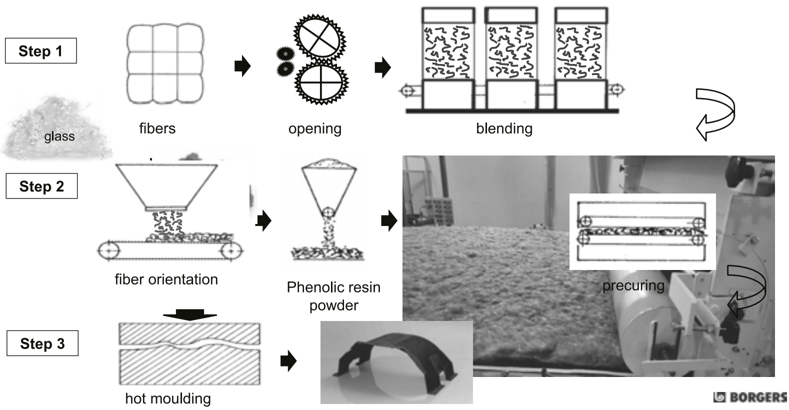
Material concepts

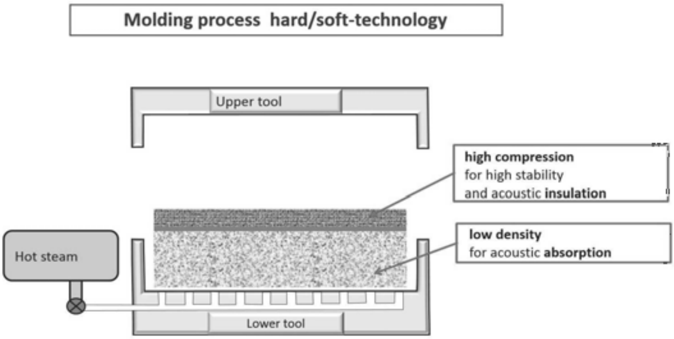


Material Concepts



Aerodynamic production process for Triflex^{mineral}





Equipment requirements

- Press
  - Valve for the steam circuit, should be in the machine periphery
- Tooling
  - The fitting of the tool should be steam tight
  - The cutting surface should be dedicated for Triflex Mineral (dimensional)
  - The cutting device itself should have a special shape based on the Triflex mineral to overcome sharp edges.
  - Steam channels have to be included.

Summary

Targets:

- Weight reduction with the Triflex mineral has achieved.
- The cost price of a part in Triflex mineral is about 15% lower as the material composition with SMC.
- The material could be used in current tooling's after some small optimizations if the tool has already a steam system included.
- The functionality of the parts is still confirm specification

A new analytical calculation method for the injection-molding process of a composite luggage rack holder

M. Bakkal, Istanbul Technical University, Istanbul, Turkey;
O. Otuz, M.Sc., **S. Doğru**, M.Sc., Mercedes-Benz, Istanbul, Turkey

Abstract

This article presents a new anisotropic analysitical method for thermoplastic composite materials. This method considers the effect of fiber orientation on the mechanical properties of composites and concludes with variouslastic modulus values of material in complicated part geometries. At the beginning of the paper, a new composite luggage rack holder is designed according to the plastic injection-molding design criteria to replace the previous metal luggage rack holder. Afterwards, Moldflow simulations and analyses are carried out, with the results of analysis including fiber orientation data. Next, fiber orientation input is mapped using Helius software. Mapped data containing anisotropic structure information with various elastic modulis are imported into ABAQUS structural software and analysis carried out. The study concludes that with this newly developed method, anisotropic structures with various elastic modulus values are mapped into finite element analysis software successfully and anisotropic analysis gives a more realistic estimate of strength and deformation results than does isotropic analysis.

1. Introduction

Polymer composite is the material which is spreading widely among industries. Especially industries such as the automotive industry, which seek to make lightweight products while providing the same strength results as with previous materials, are trying to use polymer composites. Apart from these advantages, they also have good fatigue resistance, their thermal expansion and electrical conductivity are low and they can be easily molded to produce complex parts [1]. Polymer composites vary as regards their matrix and reinforcement material. There are two different matrixes that can be used for composites: thermoplastic and thermoset. They differ from each other in respect of having cross-links and their state at room temperature [1]. There are also different fiber materials such as glass, carbon, and aramid which can be found in several forms [3]. According to their properties they are used in a variety of applications in the automotive industry. As the importance of the composites in automotive industry increases, so too does the importance of the analyses of their behaviors before becoming a real product. Fiber orientation of the composites during manufacturing and its effects on strength and fatigue analyses have in particular become one of the areas which can be researched and widely developed.

Analyses of strength and fatigue by means of finite element analysis (FEA) software has been very popular method in previous research work. With software such as Abaqus, both isotropic and anisotropic analyses can be applied and results obtained for stress and displacement. However, fiber orientation of the composites during injection molding could not be predicted with these software programs. In order to eliminate this deficiency, many programs have been produced to carry out a simulation of the process and convert of the results into FEA programs. Simulations of the injection-molding process are carried out with Moldflow, C-Mold and so on. To transfer the results from these programs, different interfaces such as Digimat and Helius have been created. Some but not many studies have been made of this aspect. They make use of various simulation and analysis programs and the interfaces which can carry out conversions between them.

Prediction of the fatigue behavior and strength of the part using both finite element analysis and mold flow software with the help of interfaces have begun to be popular. Knowing the effects of the injection-molding process on the composites and the corresponding isotropic and anisotropic strength analyses before manufacturing the part is becoming very important. Because of this, many studies are carried out using different interfaces. Kancharla et al. use the translator insideMoldflow and convert the Moldflow results to Abaqus. They try to show the importance of orthotropic analyses and their reliability using both simulation and experimental methods taking the deflection of the part as reference. According to deflection results, they found that isotropic analyses will be inappropriate for short-fiber-reinforced thermoplastics and that orthotropic results vary from experimental results by 4% [2]. In another study, Lindhult and Ljungberg investigated the fatigue behavior of the short-fiber-reinforced polymers. They tried anisotropic analyses using software such as Moldflow, Abaqus, Digimat, and nCode DesignLife. They obtained the fiber orientation by carrying out a Moldflow simulation and exported the data to Abaqus using the Digimat interface. Digimat also has been used for converting from Abaqus to nCode DesignLife. Their investigations used the front-end carrier of an automobile as a case study. According to them, conversion between programs has been successful but the correlation between simulation and the experimental results was weak. They have stated that results were consistent although they did not match completely and can be developed by making further researches [3]. Another investigation was conducted by Carlsson to investigate the relation between the injection-molding method and stress analysis of short-fiber-reinforced composites. They chose three different shapes –

specimen, plate with hole and battery tray – for strength and stiffness analyses. For the plastic simulation and fiber orientation results, the Autodesk Moldflow program was used. To make the conversion between Moldflow and Abaqus, the Autodesk Moldflow Structural Alliance for Abaqus 2012 (MSA) was selected. Carlsson wrote Matlab code in order to provide the ultimate strength value (not supplied in Moldflow) to complete the conversion. According to the results obtained, a good correlation has been seen for the stiffness analysis but when compared with the stiffness results, strength results have shown uncertainties in respect to comparison of theory and experiment [4].

In the present study, analysis of the design of the luggage rack holder was carried out on Moldflow and Abaqus software in order to observe the relevance of the results to strength. Also using the Helius interface, the realism of the method used was investigated. In order to perform flow analysis, Moldflow software, which simulates the thermoplastic injection-molding operation, was used. These results have been transferred to Abaqus using Helius, an interface produced by Autodesk. According to this procedure the results of both isotropic and anisotropic strength analysis and flow analysis are investigated.

2. Material and method

2.1. Material

A polyamide 6/6 was selected as the thermoplastic matrix composite material. Analyses were performed for non-filled polyamide 6/6, UltramidA3K, and 35% short-glass-fiber-reinforced polyamide, UltramidA3WG6. Mechanical and thermal properties of the selected materials are shown in Table 1.

Table 1: Properties of non-filled PA 6/6 and 35% glass-fiber-reinforced PA 6/6

Material	Mechanical Properties				Thermal Properties		Density g/cm^3
	Elastic Modulus (MPa)		Poisson Ratio		Surf. Temp °C	Melt Temp °C	
	E1	E2	v12	v23			
PA66 Non-filled	3100	3100	0.4	0.4	50	290	0.9463
PA66 GF35	11300	4428	0.38	0.55	85	290	1.3808

2.2. Method

Our new design of luggage rack holder in two cases is investigated in this study (Fig.1). The part was designed to achieve the goal of reducing its weight to below 1 kg. In order to achieve this, the material chosen for the part was glass-fiber-reinforced thermoplastic and it was decided to manufacture it by injection molding. The flow analyses, isotropic and anisotropic strength analyses were carried out by different software programs. The procedure for each analysis are explained in detail below.

Flow simulations for different types of injection- and compression-molding processes were carried out with Moldflow Insight 2016 software. The examination of the thermoplastic injection-molding process analysis begins with the meshing step. After meshing, injection locations and process parameters need to be set. In order to obtain more realistic results with the analyses, runner and cooling system designs can be made before starting the analyses. For reasons of manufacturability, hot runner systems were selected for the new part. There are many parameters which can be investigated once simulation of melt flow has been done. Weld lines, filling time, fiber orientation tensor, air traps, sink marks are some examples of these parameters. Finite element analysis was carried out using the commercial software ABAQUS 6.13. The study started with isotropic analysis. Material properties were taken from the software library. The selected modulus of elasticity values of the material were 5000 MPa; 11000 MPa; 19000 MPa, respectively, and the Poisson ratio was 0.35. The defined boundary conditions are shown below in Fig. 2. There is a fixed connection (zero degrees of freedom) at the upper connections and only rotational movement about the y- and z-axes permitted at the lower connections.

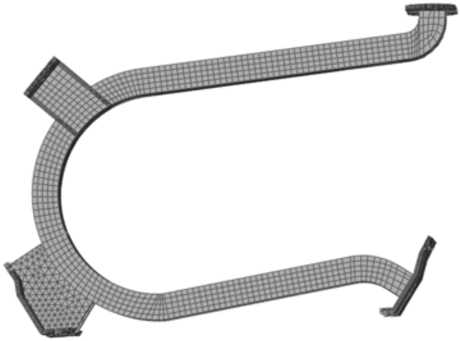


Fig. 1: ABAQUS model of the luggage rack holder

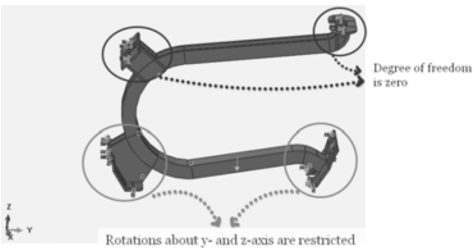


Fig. 2: Boundary conditions applied to the geometry

3. Results and discussion

The design was investigated in two different cases: no glass-fiber-reinforced PA66 and 35% glass-fiber-reinforced PA66. The 3D model of the new design is shown below in Fig. 3.

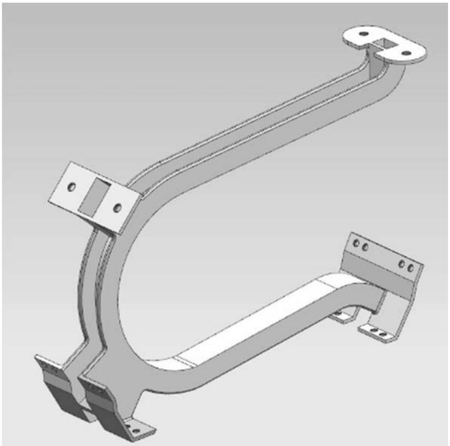


Fig. 3: Part geometry

3.1. Moldflow results

Moldflow results help us to understand the injection-molding process and the plastic injection-molded part. To analyze the design, the strength properties of the material must be specified for the FEA program. In this study, the Moldflow database was used for the workpiece's material properties.

a. Fiber orientation tensor results

The fiber orientation results show fiber orientation through the plastic injection molding. Orientation in one direction means that fibers are fully orientated in the direction of the plastic flow. However, orientation in one direction is nearly impossible with thermoplastic composites. Generally, the area where melt is injected through the gates shows irregularity with respect to fiber orientation due to divergent flow in that region [7]. It can be seen from Fig. 4 that regular orientation decreases significantly in the part in the gate area compared with other regions. The fiber orientation results can also used to investigate the strength of the plastic injection-molded part. The fiber orientation tensor value observed is 0.8835 ('1' means fully oriented fibers) for the fiber orientation in the direction of the flow.

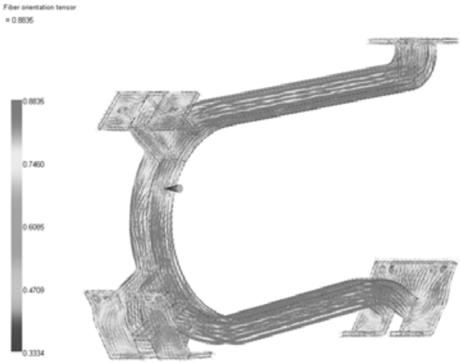


Fig. 4: Fiber orientation tensor for 35% glass-fiber-reinforced PA 6/6

a. **Weld line results**

Weld lines occur where melt flows coming from different directions meet. Generally speaking, the weld line gives an indication of areas which are structurally weak [7]. In addition, surface appearance is affected adversely. For that reason, consideration should be given to regions where the weld line occurs, especially in the case of applications in which part strength and the appearance of the surface are important. The negative effects of the weld line can be prevented by modifying the part geometry, process parameters and mold design [8]. Coloured areas in Fig. 5a and Fig. 5b represent the weld line where two different materials meet.

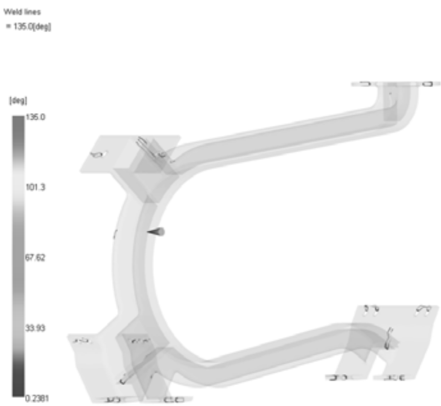


Fig. 5a: Weld line results for non-filled PA 6/6

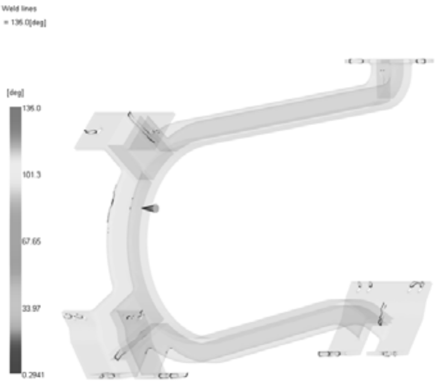


Fig. 5.b: Weld line results for 35% glass-fiber-reinforced PA6/6

b. Average Volumetric Shrinkage Result

Volumetric shrinkage shows the percentage raise of local density starting from the end of the packing time until the time it solidifies to the ambient temperature. Volumetric shrinkage has to be uniform to prevent the warpage. On the other hand, average volumetric shrinkage indicates the mean value of volumetric shrinkage through the half-gap thickness. This value can be used for the detection of the sink marks on the surfaces [9]. Fig 6.a and Fig 6.b shows the average volumetric shrinkages percentages for non-filled PA6/6 and 35% short-glass-fiber-reinforced PA6/6, respectively. According to the results, when the non-filled material is used, the value is seen as 14,86% while in the case where glass-fiber-reinforced material is used, average volumetric shrinkage has reduced to 11.81%. This result suggests that reinforcement with fibers reduces the average volumetric shrinkage.

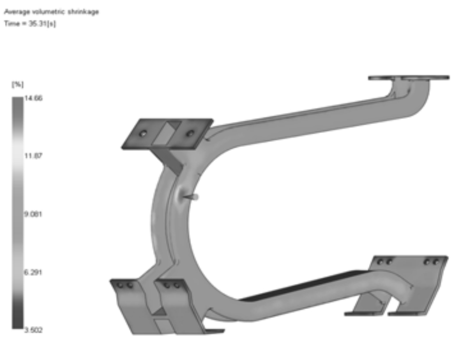


Fig. 6.a: Average volumetric shrinkage results for non-filled PA 6/6

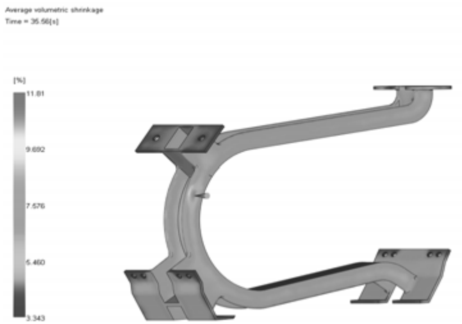


Fig. 6.b: Average volumetric shrinkage results for 35% glass-fiber-reinforced PA6/6

c. Air Trap Results

The air trap value indicates the air that is caught within the injection-molded part. Generally, it reveals the presence of defects on the surfaces. Although it causes problems on surfaces, such as burn marks, short shot, surface blemishes and voids, some of them which are near the surface can be eliminated with the proper venting during the injection-molding process. Air traps can be prevented by changing part and mold design and setting proper molding conditions [8]. In Fig. 10.a and Fig. 10.b it shows that short-glass-fiber reinforcement in PA6/6 does not make any significant changes to the air trap results and all of them are near the surface, which can be prevented by appropriate molding conditions and venting.

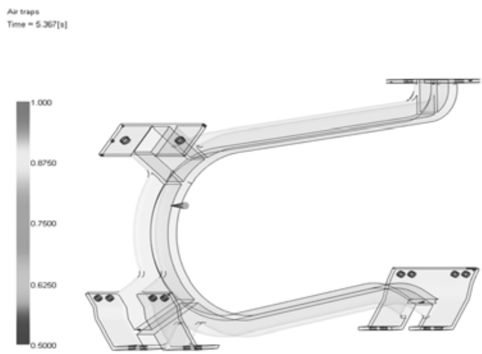


Fig. 7.a: Air trap r for non-filled PA6/6

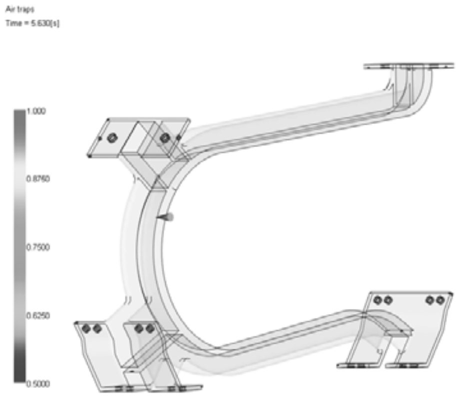


Fig. 7.b: Air trap results for 30% glass-fiber-reinforced PA6/6

3.2. Isotropic Analysis Results

The design selected for the luggage rack holder is modelled using different Young's modulus values in isotropic fashion in order to evaluate critical regions. 5000 MPa, 7800 MPa, 11000 MPa and 17000 MPa are selected as critical strength values for the material PA66%35 GF. Isotropic analyses will be used to make a comparsion with anisotropic calculation results and frequency response analyses (vibration) results.

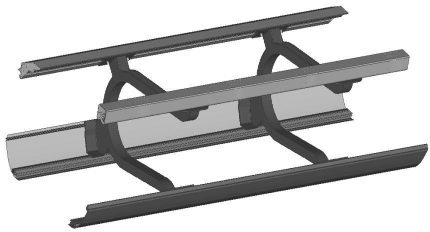


Fig. 8: Finite element model of the luggage rack system on Intouro buses

The luggage rack system was modelled with solid elements such as hexahedral and tetrahedral elements. By using solid elements for rack holders it was easier to simulate real deformations and stresses in the desired product.

In order to fix the rack system as in the real bus, rigid elements were applied on two sides of the upper horizontal profiles and loads were applied to different positions on the front profile, as can be seen in Fig. 9.

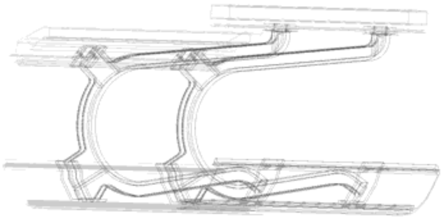


Fig. 9: Bolt connection regions on the luggage rack holder

Bolts were applied to eight different positions and were fixed by pre-tension forces, which were taken from Daimler Screw standards (Fig. 9). Firstly, critical deformations and stresses are examined, then pre-tension effects analyzed.

Two different load cases were applied in the first step of finite element analysis. Pre-tensions were applied to all of the bolt connections in order to obtain a more realistic bolt strength evaluation. In order to examine the real bus conditions, luggage masses were also taken in consideration, so that simulations were carried out either with a luggage effect or without a luggage effect. The results show us that the main critical region is located on the connection parts of the holder, since bolts are used to provide connections at these positions.

Additionally, stresses become higher on these connection parts, especially near bolt holes, as shown in Fig. 10, which indicates that pre-tension should be examined in detail in order to develop the geometry more accurately.

Fig. 10: Von-Mises stress results after a pre-tension load on the bolts

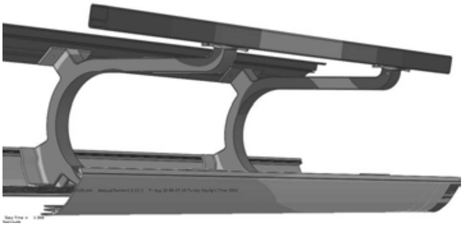


Fig. 11: Deformation results after a pre-tension load on the bolts and applied loads

After applying pre-tension to the bolts, the rest of the loads were applied from specific regions on the luggage rack system. In Fig. 11, limitations for geometrical deformation can be evaluated so that deformations obviously increase and become critical on the back side of the holder. It is easily predicted that screws and bushings will be affected immediately by both pre-tension and applied loads; afterwards stresses propagate into the structural regions of connection holder parts. FEAs were prepared as four cases; firstly, with the lowest E module and without luggage; secondly, with the lowest E module and with luggage; thirdly, with the highest E module and without luggage and, finally, with the highest E module and with luggage. Considering static FE analyses, the worst case was with the lowest E module and with luggage, whereas the best case was with with the highest E module and without luggage. After adding luggage as it is stowed in real Intouro buses, the results from static FEAs demonstrate approximately 15 - 20% higher stresses than the results without luggage on the system. Fig. 12 and Fig. 13 illustrate comparative von-Mises stresses and on the central C-shape of the holder there occurs the biggest difference at around 22%. Luggage has an average mass of 300 kg as in real conditions and it seems that it has a normal impact across the holder's section.

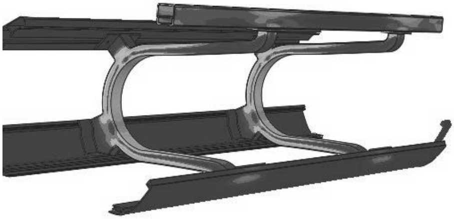


Fig. 12: Von-Mises stress results after applied loads, with maximum E module value but before adding luggage (17000 MPa)

Fig. 13: Von-Mises stress results after applied loads, with maximum E-module value after adding luggage (17000 MPa)

Fig. 14 and Fig. 15 demonstrate the static FEA results under von-Mises conditions and with the lowest E module value of 5100 MPa. In a comparison with the results of the highest E module and the lowest E module, 15 – 45% differences can be captured, close to areas of back-side connection parts particularly.

After adding luggage as it is stowed in real Intouro busses, results from static FEAs show approx. 15 – 30% higher stresses than the results without luggage on the system. Fig. 14 and Fig. 15 illustrate comparative von-Mises stresses and either on the middle C-shape of the holder or in the close vicinity of connection parts the biggest difference of around 25% is found.

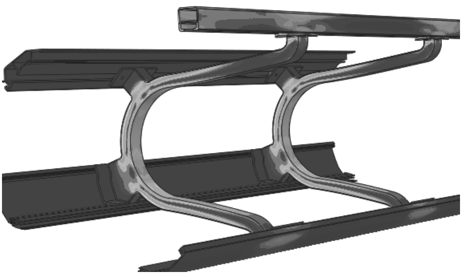


Fig. 14: Von-Mises stress results after applied loads, with minimum E-module value before adding luggage (5000 MPa)

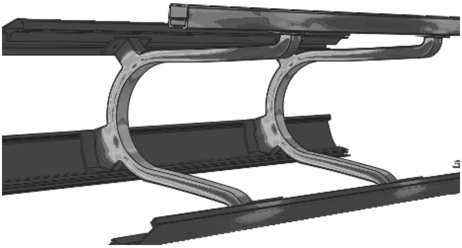


Fig. 15: Von-Mises stress results after applied loads, with minimum E-module value after adding luggage (5000 MPa)

3.3. Isotropic Modal Frequency Analysis Results

Parallel with strength analyses, modal frequency analyses should be conducted in order to understand the dynamic behavior of the luggage rack holder under different levels of vibration. Especially for those products which can be damaged not only under high loads but sometimes under minor loads with many repetitions, critical damage to and cracking of the product can occur.

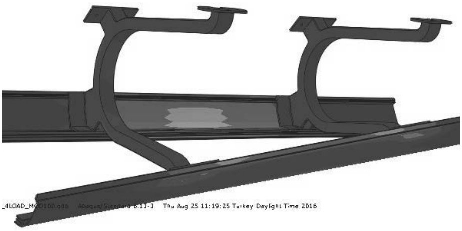


Fig. 16: Frequency response function (FRF) results at 7 Hz without luggage

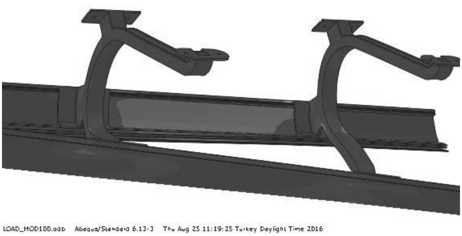


Fig. 17: Frequency response function (FRF) results at 10 Hz without luggage

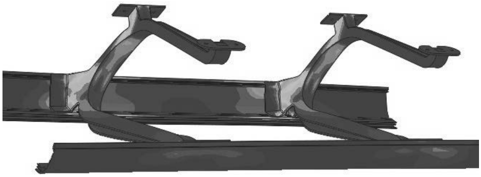


Fig. 18: Frequency response function (FRF) results at 30 Hz without luggage

FRF results are separated into two groups: vibration results without (Figs. 16 - 18) luggage and with luggage (Fig. 19 - 21). All the simulations were carried out with the lowest E module in order to reveal the most critical region on the rack system and the holder. Among the first group of simulations, the frequency range was between 7 Hz and 85 Hz, which it should be taken as the worst case, since the system has no additional mass and the holder has the weakest material property of PA66 %35 GF. Vibration results should be examined according to their frequency range pairs in order to validate with the aid of measurements and following this to eliminate these critical frequencies. The most critical range was between 6 Hz and 31 Hz. That means with or without luggage, frequencies have to located outside these intervals. If there are some critical frequencies between 6 Hz and 31 Hz, some geometrical solutions should be found which reduce the critical frequencies.

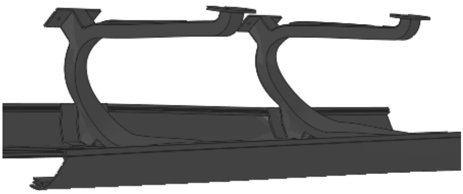


Fig. 19: Frequency response function (FRF) results at 7 Hz with luggage

Fig. 20: Frequency response function (FRF) results at 11 Hz with luggage

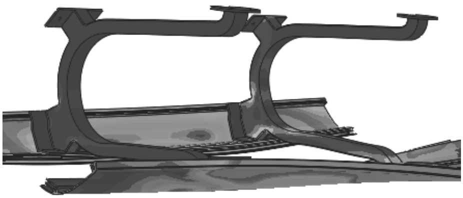


Fig. 21: Frequency response function (FRF) results at 30 Hz with luggage

FRF analyses indicate that there are huge differences between two simulation groups, without and with luggage effect.

Moreover, these results show that the luggage effect has a big impact by changing the dynamic behavior of holders in the rack system and the frequency range between 6 Hz and 85 Hz was obtained during the simulations without luggage, whereas 6 Hz and 31 Hz originated as the frequency range during simulations with luggage. These numbers demonstrate that frequencies 7 Hz, 10 Hz, 18 Hz and 30 Hz have to be dispelled by changing the geometry.

3.4. Anisotropic Analyses Results

Anisotropic material modeling of short fibers was carried out using firstly, Moldflow for the injection-molding process and, secondly, Helius for the mapping between Moldflow and ABAQUS and finally ABAQUS for anisotropic simulations and visualizations. Relatively different stresses occur in both von-Mises (Fig. 22) and max. principal conditions (Figs. 23 - 24). Region by region the holders were examined and it was found that the middle C-section has the most critical and flexible positions, which means there are some hot-spot points which do not occur with the isotropic modeling technique. Differences are calculated at around 15 – 20% for critical positions, such as the middle C-shape section and the close vicinity of bolt holes.

Results indicate that anisotropic material modeling improves the evaluation of short-glass-fiber-reinforced injection-molded composite products such as the luggage rack holder. Failure energy falls on the mid-region of the holder and this tells us that this region has to be modified. Not only von-Mises stresses but also max. principal stress results demonstrate that 60% of critical regions are found in the same location – the mid-region of the C-shape, either by average stress results or by principal stress results.

Fig. 22: Anisotropic von-Mises results with Helius

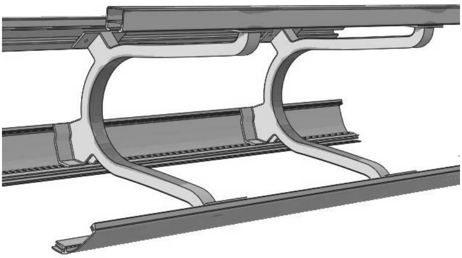


Fig. 23: Anisotropic max. principal stress results with Helius

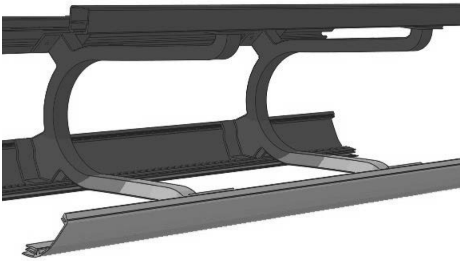


Fig. 24: Anisotropic max. deformation results with Helius

Conclusion

This paper aims to study the effects of different loading and material conditions, including luggage effect, isotropic and anisotropic material modeling module criteria, on the mechanical responses of the short-glass-fiber-reinforced injection-molded composite luggage rack holder under static loads and dynamic vibrations. The isotropic material modeling and static FE calculations are established using ABAQUS PYTHON scripting language. An anisotropic material distribution among short glass fibers is developed by using Moldflow, Autodesk Helius and ABAQUS interfaces. Vibration analyses and frequency response function (FRF) calculations were established using ABAQUS PYTHON scripting language. From numerical analysis of the injection-molded composite product with different materials, loading and boundary conditions, four main conclusions are obtained:

(a) In general, major hot-spot points above the limit value are located on the C-shaped middle region of the rack holder. Cracks start in the the mid-region and propagate non-symmetrically to the top and the bottom sides.

(b) Pre-tension was applied at eight different bolt locations with same amount of torque. After applying torque to the bolts, high stresses over yield strength were captured and high inter-contact shear stresses occur which directly affect the behavior of the bolt connection.

(c) The first critical frequency 7 Hz is obtained either with the luggage case or without the luggage case. Moreover, these results show that the luggage effect has a big impact by changing the dynamic behavior of holders in the rack system. The frequency range between 6 Hz and 85 Hz was obtained during the simulations without luggage, whereas 6 Hz and 31 Hz originated as a frequency range during simulations with luggage. These numbers demonstrate that frequencies 7 Hz, 10 Hz, 18 Hz and 30 Hz have to be dispelled by changing the geometry.

(d) Anisotropic material modeling of short fibers was carried out using firstly Moldflow for the injection-molding process, secondly, Helius for the mapping between Moldflow and ABAQUS and finally ABAQUS for anisotropic simulations and visualizations. Relatively different stresses occur under both von-Mises and max. principal stress conditions. Region by region the holders were examined and it was found that the middle C-section has the most critical and flexible positions, which means there are some hot-spot points which do not occur with the isotropic modelling technique.

Although isotropic static analysis criteria theoretically show some advantages by minimizing details and revealing hot spots easily, there are still some intractable problems, such as accurate determination of the dynamic fracture location during low levels of vibration and related strength parameters. Because of simpler formulas and numerical implementation by FEA, we also examine vibration and frequency response function criteria, which are widely applied to the FRF analysis of composites as an integrated module in some commercial finite element software including ABAQUS, LS-DYNA and MSC Dytran. By weighing numerical precision and cost, there should be an appropriate selection and use for these failure criteria in the impact analysis of composites.

Overall, these calculation and simulation criteria as macroscopically phenomenological theories should make it possible to solve some practical failure problems of composite structures accurately and efficiently.

2. References

1. Kancharla A. K., Sharma H. K., Nugent P., Orthotropic structural analysis of short fiber filled thermoplastics: Abaqus – Moldflow interface, Experimental validation, SIMULIA India Regional Users Meet 09
2. Kancharla A. K., Sharma H. K., Nugent P., Orthotropic structural analysis of short fiber filled thermoplastics: Abaqus – Moldflow interface, Experimental validation, SIMULIA India Regional Users Meet 09
3. Lindhult J., Ljungberg M., Fatigue analysis of anisotropic short fibre reinforced polymers- by use of digimat and nCode Designlife, Chalmers University of Technology, Gothenburg, Sweden, 2015
4. Carlsson J, Coupling of injection moulding process to stress analysis of short fibre composite structures, Chalmers University ff Technology, Gothenburg, Sweden, 2012
5. Strong A.B., Fundamentals of Composites Manufacturing - Materials, Methods, and Applications, 2nd ed., SME, 2008
6. Groover, M.P., Fundamentals of Modern Manufacturing: Material, processes and Systems, 3rd ed. John Wiley & Sons Inc., New Jersey, 2007
7. Imihezri S.S.S. , Sapuan S.M. , Sulaiman S. , Hamdan M.M., Zainuddin E.S., Osman M.R., Rahman M.Z.A. , Mould flow and component design analysis of polymeric based composite automotive clutch pedals, Journal of Materials Processing Technology, 2005
8. Shoemaker J., Moldflow Design Guide : A Resource for Plastics Engineers (1st edition), Massachusetts, 2006
9. Autodesk Moldflow webpage

True confidence in thermoplastic composite simulations for any automotive component

W. Schijve, **G. Francato**, **R.Yaldiz**, SABIC, Geleen, The Netherlands

Abstract

Today, carbon emissions reduction is one of the key drivers for new developments in the automotive industry. Amongst others, one solution is to reduce the weight of a vehicle significantly. Composite materials can offer these weight savings, yet widespread adoption is as yet lacking. We believe that cost hurdles can be overcome by using UD or multi-axial laminates in combination with an overmolding process with LFT material.

Besides cost, a major hurdle that we see is the lack of confidence in performance predictability. Especially for the more cost-efficient hybrid combinations of UD-tape-based laminates with overmolding material, robust predictability procedures are not yet state of the art.

For this reason, a test component was designed that can be produced in a representative production process and can validate all of the many different composite failure modes. The main purpose is to have sufficient process and simulation validation for any yet-to-be-designed component. At the same time, the design takes care to ensure the actual failure occurs in the continuous-fiber composite material and not in the much weaker short/long injection-overmolding material. Current simulations now show good agreement with test results and as such give confidence in predictions.

1. Introduction

Continuous-fiber-reinforced thermoplastic materials have been attracting the attention of the automotive industry for several years now. They are attractive due to their high mechanical performance and low weight. These new materials do however require new, robust manufacturing processes which must comply with the short cycle times of around one minute required for mass production in this industry. In addition, new predictive methods need to be developed providing the necessary confidence for accurate predictability of the manufacturing process and (mechanical) part performance.

A few years ago, SABIC interviewed most major OEM's, tiers and equipment suppliers, asking them what they see as the main hurdles for the introduction of composites. This resulted in a clear top three:

1. Design predictability.
2. Cost
3. Cycle time

Of much less importance were the following aspects:

- Material properties characterization
- Joining predictability / performance
- Quality and consistency
- Recycling

2. Cost-effective material forms and process

We believe that the issue of cost and cycle time can be handled especially well by clever design and making use of the hybrid overmolding technology as explained elsewhere [1, 2]. The advantage of this process, when properly designed, is that it significantly reduces the percentage of composite material, maximizing the use of the cheaper overmolding resin. This is explained further in Figure 1.

In this approach, high-performance multi-axial UD tape-based laminates are used selectively along the main load axis. At the same time, functional details can be integrated, using the injection-molding material, eliminating separate production steps. In this way, the same high mechanical performance of thermoset composites can still be realized, without the high cost associated with these materials.

The hybrid overmolding process itself is schematically shown below (see Figure 2) and by now has been well developed for industrial use [4].

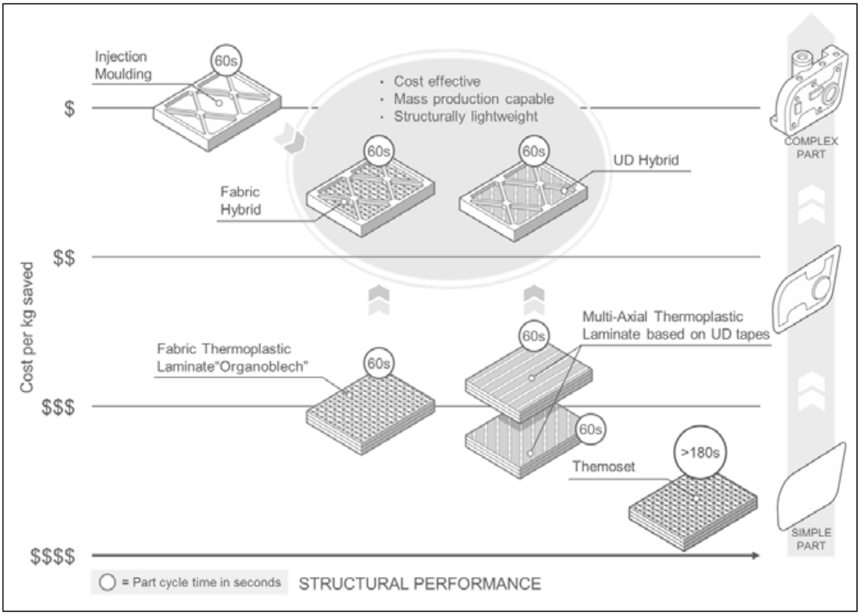


Fig. 1: Performance versus cost of weight saving for various material systems.

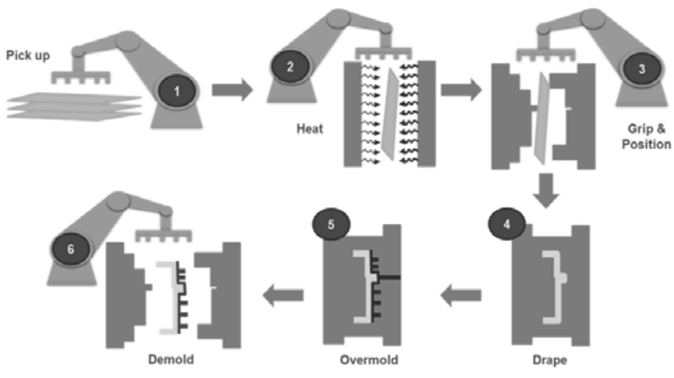


Fig. 2: Hybrid overmolding technology for thermoplastic hybrid components. 1: Pick-up of composite blank. 2: IR heating. 3: Blank fixation in the mold. 4: Thermoforming of blank. 5: Injection overmolding. 6: Part demolding

As regards the composite material form, we see multi-axial laminates made from UD-tape material of constant thickness as being the most suitable for automotive applications, since UD layer orientations can be best optimized to load paths and thus are most efficient for weight saving.

SABIC has developed UD tapes, using various resins and fibers, and multi-axial or uni-directional laminates and can offer a wide range of fully compatible overmolding products. A first UD tape product is called UDMAX™ GPP 45-70 tape, based on glass-fiber-reinforced polypropylene (see Figure 3).

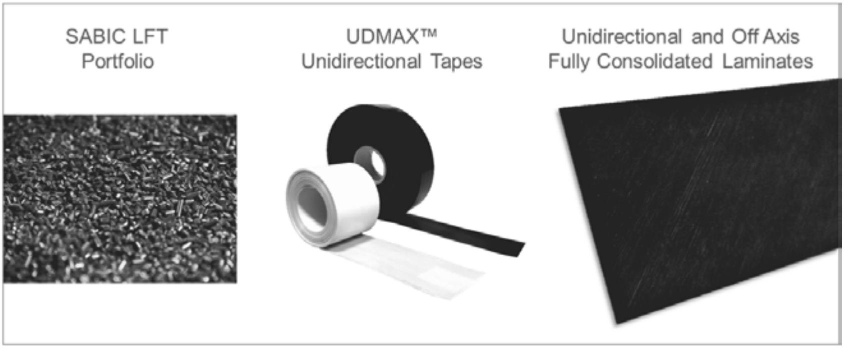


Fig. 3: SABIC composite material portfolio.

The material has 45% glass fiber by volume, which corresponds to 70% fiber by weight. In addition, molding and application development support can be provided, which includes the expertise and capability needed to predict a part's mechanical behavior [3]. Note that fabric-based materials are also evaluated, which may involve specific applications not discussed here.

Although unidirectional tapes are commercial products too, multi-directional laminates will be by far the more cost-effective solution for automotive use because the material supplier can produce them on a large continuous scale. In contrast, tape-laying systems will always take a few seconds per deposited piece of tape, and an automotive-sized laminate will take many minutes to manufacture. Also the flexibility to make large-width laminates, up to about 2 meters, in any width or length, gives good nesting options to minimize waste. Note that off-axis plies deposited with a tape-laying machine or pick-and-place units in many cases still results in waste. This is illustrated with an example in Figure 4 below.

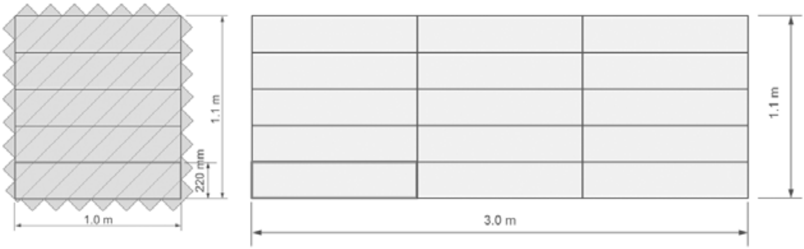


Fig. 4: Tape-laying solution for 220x1000mm multi-directional blank manufacture (left); the laminate solution (right).

Suppose we would need a blank with dimensions of 220 x 1000 mm, 4 mm thick with a typical mix of 0° and ±45° layers, as for example could be used for a door impact beam. A fast tape-positioning system using 100 mm wide tape would need to deposit 208 pieces of tape to make a total laminate that can be used to cut out five blanks at a later stage. As a result, even the fastest system available today would need more than one minute per blank. On the other hand, multi-directional laminate plates mass-produced by the material supplier to optimal size would just need nesting and cutting of the blanks. And in the case of a rectangular blank, as in the above example, practically zero waste is the result. The important conclusion here is that for mass production, with cycle times of one to two minutes, you already would need one tape-laying/positioning machine for each relatively small part, with the associated investment cost and floor space. So large, optimally sized laminate plates with the required lay-up would be the better option.

As an application example, consider the cross-car beam, shown in Figure 5, carrying the dashboard, steering wheel and a number of components. For the existing C-class car model, this application was an aluminum-welded assembly consisting of about 20 separate sheet metal and one casting part. Note that most mass-produced cars in the same class today would be made of steel rather than aluminum.

The part was redesigned for a composite overmolding process, as a one-shot molded component, as shown in Figure 5 on the right. Although it may look rather different, the same equipment can still be mounted and can still fit in the same available space.

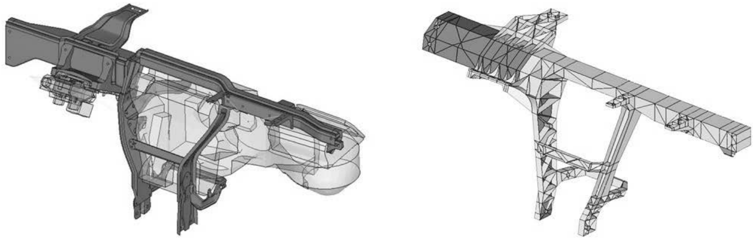


Fig. 5: Reference metal (left) and composite (right) cross-car beam. Only the left part of the composite beam has UD tape laminate (dark colour).

The dark grey parts indicate the use of multi-directional composite laminates, while the light grey parts represent the overmolding material, in this case a 30 wt% long glass PP material. The main design driver for this part is the lowest eigenfrequency, which is a driver for vibrations which can be felt on the steering wheel. As the steering column is a heavy part, stiff support provided by the cross-car beam is crucial. The laminate in the section supporting the steering column will need both the 0° and ±45° directions of UD tape to provide both the bending and torsional stiffness in this section.

The composite part was optimized for equal performance at 65 °C, which includes a first eigenfrequency of higher than 43 Hz at this temperature. Although this temperature hardly influences the continuous-fiber composite material as the fiber stiffness does not change with temperature, it does have some effect on the overmolding material, where the influence of matrix properties is much greater. In the optimization, these effects have been taken into account, based on measured data.

Furthermore, although the actual reference component happened to be an aluminium beam, the same beam was also optimized separately as a steel sheet-metal assembly and as a magnesium casting, such as can be seen on premium car models today. Figure 6 shows the results of weight optimizations using various material forms. It should be noted again that each of the composite variants has exactly the same mechanical performance as its metal counterparts.

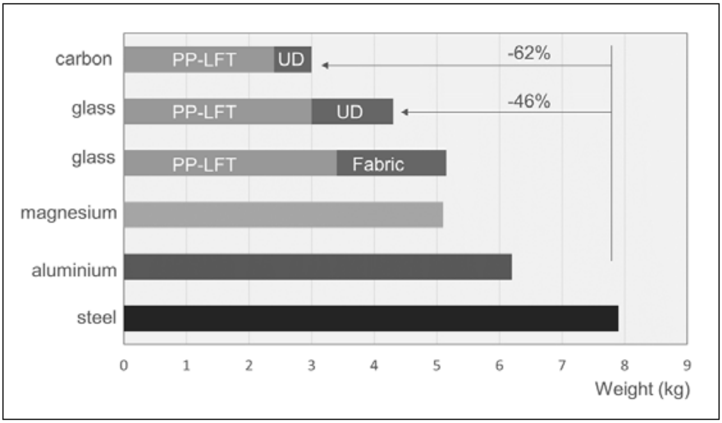


Fig. 6: Cross-car beam weights for various materials.

In Figure 6, the PP-LFT segments indicate the amount of overmolding material, the other segments show the amount of continuous-fiber material. Clearly, the majority of material is long-fiber thermoplastic (LFT) overmolding material, which dilutes the cost for this component significantly.

Compared to the steel solution, a weight saving of four to five kg is possible, depending on the choice of carbon or glass fibers. Looking at the $/kg weight-saved value, glass fiber is the more favorable alternative and compares very well with weight-saving alternatives considered by many OEMs, such as magnesium or aluminium. In this case, one could even consider use of carbon fiber because the amount of material needed is very small. Being a stiffness-driven design roughly one third of the amount of carbon fiber would be needed as compared with glass. Despite this, the glass variant would still be the more attractive today.

3. Confidence in predictability

Although, as shown above, the cost and cycle-time hurdles can be overcome and hybrid thermoplastic composite components are quite cost-effective, confidence in predictability still needs to be gained. For this reason, a beam-like test component was designed which would tackle variations in process and validate predictions of actual in-part composite material performance.

Confidence in predictions of composites can be obtained at various levels (for example, one would usually start with testing material properties on laminates, and end up with testing a final component until failure under realistic application conditions). This could be, for example, a side door in a car, tested in a crash situation. This is illustrated below (see Figure 7).

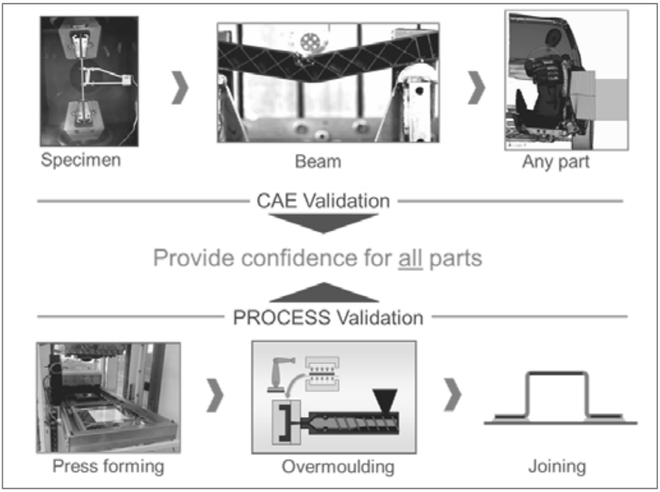


Fig. 7: Performance validation steps in component development.

Composite material properties would typically be tested on the as-supplied material, this being constant-thickness laminates. To obtain all necessary failure parameters this would be carried out with unidirectional composites, testing the material in tension, shear and compression in different orientation directions. This will yield the required material properties and the variability of these properties.

Next, it is important to realize that the material will see a processing step, typically some kind of press forming, sometimes also called drape forming. And in the case of a hybrid process this is followed by an overmolding process. These processes can add variability to the material properties, and therefore the effect of process variations within a given window should be determined experimentally also.

Finally, the accuracy of simulation methods themselves needs to be verified, preferably on a component that can be tested under different temperatures and speeds. At the same time this component should undergo a production process that is representative of the final applications to be developed in the future.

Now it is essential to note that for a general validity for all possible components, one should be able to test each individual composite's failure mode on this test article (for example, being able to test both composite tensile and compression failure).

Covering all these boundary conditions, a single test component was developed as a four-point bending beam having a hat-shaped or 'omega' cross-section (see Figure 8).

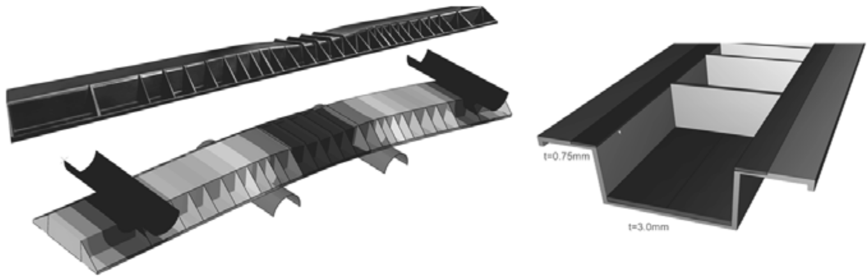


Fig. 8: Four-point bending hybrid test component. Note the depression in the middle test section. Right: 3D cross-section showing highly asymmetrical UD insert layout (dark grey).

As shown in the illustration, the beam has reduced height at the middle test area. This is necessary in order to have a well-controlled test region and to make sure that the highest stresses do not occur very locally, only below the load introduction points. However, this depression in the height of the beam easily leads to buckling at the high failure stresses as typically seen for UD materials. For this reason, the final geometry design has an unusually large number of ribs.

The next challenge was to be able to test both the compression and tension strength of pure UD composites with this beam. A typical glass thermoplastic UD material would have a tensile strength of around 900 to 1000 MPa and a compression strength of only 500 MPa. As a result, beams loaded in bending typically always fail in compression, making it impossible to validate the tensile strength for a real component. To solve this issue, a highly asymmetrical insert layout was chosen (as in Figure 8, right-hand image).

In this way the neutral axis in bending is shifted towards the thick insert, causing the stresses in the thin insert to always be much more than twice those of the thick insert. In this way the thin UD strip can always be tested either in compression or in tension.

As can be seen in Figure 8, the beam is quite slender. Its actual length is 1000 mm while the height is only 40 mm. The reason being that in this way the shear stresses in the overmolding material remain quite low, and can be as low as around 20 MPa depending on the resin. By increasing the length of the beam, it will be certain that the beam can be tested to, for example, 1000 MPa tensile failure in the composite and not fail in the overmolding material.

Similarly, when one wants to test the shear strength, it is easy to reduce the distance between the load point and supports, which will result in relative high shear stresses.

Apart from UD strips, even multi-directional laminates or joined components can be tested for validation purposes (see Figure 9).

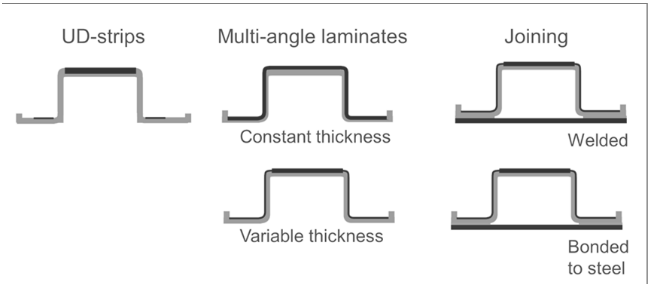


Fig. 9: Various layout configurations.

4. Example validations

Beams were tested at the typical temperatures required by the automotive industry, such as -40 and +85 °C, with both static and dynamic loading. A few examples are given below.

The first configuration using narrow strips (upper left in Figure 9) was used to test UD material performance in a real molded component, both in tension and compression by testing the beam with the hat section pointing upwards or downwards. The resulting force deflection curves can be seen in Figure 10 below. Results show that the stiffness of the beam and failure of the UD laminates can be well predicted and that the tensile strength of the UD material is much higher than the compressive strength.

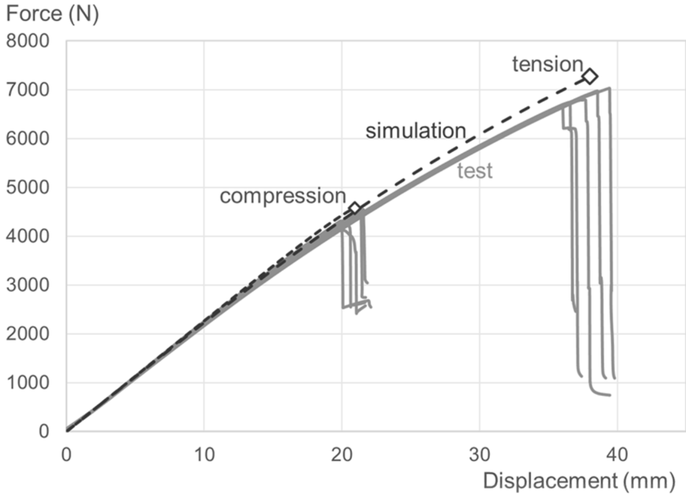


Fig. 10: Room-temperature force deflection curve for variant with narrow UD strips, loaded in either tension or compression. Solid lines are test results, dotted lines simulation.

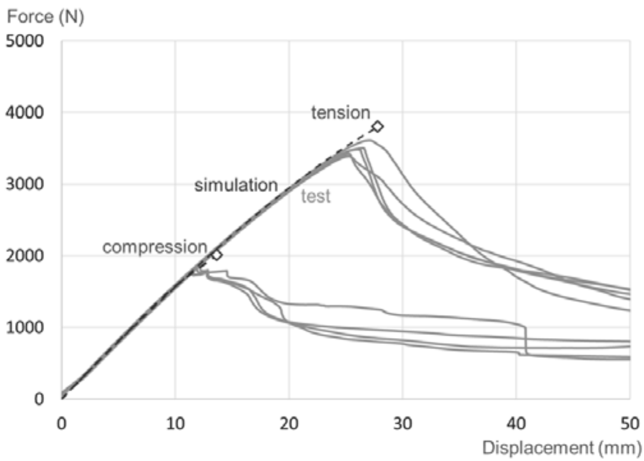


Fig. 11: 85 °C temperature force-deflection curve for variant with narrow UD strips, loaded in either tension or compression. Solid lines are test results, dotted lines simulation.

The same tests were also performed at 85 °C, as shown in Figure 11. The stiffness and force levels are now lower, as both the overmolding material and especially the compression strength fall with temperature, while at the same time the failure is now much more ductile. The important point is that there still is reasonably good agreement with predictions. Current simulation work focuses on predicting behavior past the failure point and results will be published at a later date.

5. Integrated simulation chain

Today several software packages are available for simulation of different composite manufacturing processes and for mechanical analysis. For hybrid processes, fiber orientation of both the short and the continuous fiber is especially important for mechanical (or warpage) simulation. The continuous-fiber material orientation can change due to the draping process, which can be simulated with software such as AniForm† or PAM-FORM†, while the short- or long-fiber orientation resulting from the filling process can be predicted by, for example, Moldflow† or Moldex3D†. Software packages such as Digimat† can transfer fiber orientation from Moldflow to Abaqus, which is used for mechanical performance prediction. Nevertheless, today there is no software that couples any step in the manufacturing process with mechanical simulation. At SABIC the newly developed software SIMAN† Mapper is used which takes care of all these tasks (see Figure 12). This software is a new custom development from the INPRO company.

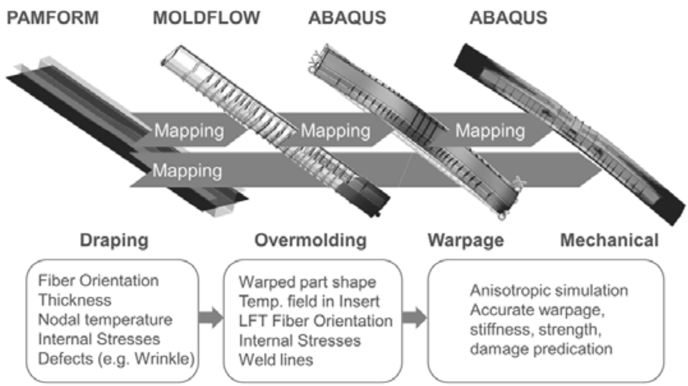


Fig. 12: Integrated simulation chain, using mapping software.

What is unique here is that these coupled simulations can be performed on 2D meshes throughout the process. This is a big advantage in design stages when one wants to optimize many different structural design layouts rapidly.

6. Conclusions

Cost-effective composite material forms, such as multi-axial laminates based on UD tape have been developed. In combination with LFT overmolding material they can offer significant lightweighting at competitive cost. Confidence in new technology still needs to be built up, especially in the case of simulations.

For this reason, a new test component has been developed. The unique geometry of this component permits validation of the different failure modes which can occur in composite materials. It will not experience the buckling failure seen with many other test beams.

Because of this special layout, it has the capability to test high-strength UD materials until failure, and as such it will be useful for any future real automotive application.

References

[1] Schijve, W., G.Francato, G.: New thermoplastic composite solutions to make automotive lightweighting a reality. ICC 2015

[2] Schijve, W., Kulkarni, S.: New thermoplastic solutions making the difference in automotive lightweighting. SPE-ACCE 2016

[3] van Aken, H., Schijve, W.: Weight saving potential of thermoplastic unidirectional composites in the passenger door of a car. ICC 2015

[4] Götze, C., Böhme, P., Rietman, B., Boxus, E., Fenske, S., Schierl, S.: Heiße Laminate sicher im Griff. Kunststoffe 106 (2016) 9, pp. 165-169.

† Any brands, products or services of other companies referenced in this document are the trademarks, service marks and/or trade names of their respective holders.

Cost efficiency through the use of UV-resistant plastics in dynamically and statically highly-stressed components

What really happened!

Dipl.-Ing. (FH) **C. Bauer**, Dipl.-Ing. (FH) **H. Häberle**,
MAN Truck & Bus AG, Munich

Abstract

Requirements for plastics in the commercial vehicle sector are hard: plastics are brought to their limits not only by service lives considerably longer than of cars but also by their very high loading profile. Very high acceleration forces well into the double-digit G range are experienced in particular by components attached to the truck frame which means that generally speaking high-grade and insensitive plastics must be used here.

Until now PET/PC blends have been used at MAN for large panel components in the bumper area. Their higher strength as compared with standard plastics was the decisive factor here. The disadvantage of insufficient UV resistance was solved by painting the components. In order to save the cost of painting for the black central area during a redesign of the plastic bumpers of the heavy TGS/X series, the blends were now to include ASA. Lower strength and toughness had to compensated by a clever design. This applies in particular to the large center section. With an unsupported span of 1.5 m, length variations of approx. ±10 mm occur in hot and cold conditions. To permit this change in length to occur without causing damage, various concepts were examined: 'floating' attachment points with selective freedoms of movement, crowning of the components, and the appropriate coordination between the unreinforced blends and the glass-fiber-reinforced load-bearing components. A structural component with a higher glass content has the positive effect of greater stiffness and the negative effect of lower longitudinal expansion compared with the unreinforced panels connected to it by welding. An optimum solution was achieved here by simulation and validation.

The goal of a reduction in system cost was achieved, firstly, by the material cost savings due to the lower relative material costs of ASA as compared with PET/PC, and secondly by the omission of painting. With the switch to ASA a robust design was created which meets all the requirements.

Lightweight carrier system for the air filter of the Mercedes-Benz Actros

Cost and weight savings – High dynamic durability

Dipl.-Wirt.-Ing. (FH) **H. Hauke**,
BBP Kunststoffwerk Marbach Baier GmbH, Marbach am Neckar

Efficiency, reduction of emissions and increases in payload are central to efforts in the commercial vehicle sector. Development work is being rigorously pursued in all areas which help improve efficiency in modern commercial vehicles. In addition to optimizations of the drive train, reduction in rolling resistance and air resistance, we have recently seen the arrival of driving management systems for fuel saving.

The empty weight of the vehicle is an important component in modern commercial vehicle utilization. A low curb weight contributes to reducing fuel consumption and at the same time to increasing the payload.

This is where the new lightweight carrier system for the clean-air filter of the Mercedes-Benz Actros comes in. As part of a lightweighting initiative an existing carrier system is to be replaced by an innovative plastic. The goal is to achieve a 45% weight saving coupled with cost savings.

The carrier system must not only carry the 6.1 kg air filter – which can become 1.5 kg heavier due to filtrate –but also receive the fenders, which can weigh up to 3.3 kg on account of snow and slush accumulation. The turbocharger is positioned close to the carrier system and irradiates the carrier system with temperatures up to 135 °C. Statically a step-on load of 100 kg must be accommodated when the air filter is stood on during maintenance work on the vehicle.

In commercial vehicles with significantly higher mileages than is the case with cars, carrier systems of this size are new territory which needs to be opened up.

Even in commercial vehicles, metals can be replaced by polyamides reinforced with high proportions of glass fiber. Starting from the space available, the principle load paths are determined using a topology model. A shell model can then be created and, derived from this, the first structural concept. A wall-thickness optimization is carried out with the structural model in order to exploit all lightweighting potential. Plastic should be used primarily along the highly-stressed tension and compression areas. The ribbing should be kept as thin as possible.

Working out the shell model is followed by a component design which best suits the plastic and the tooling. Cropping due to adjacent components must be taken into consideration as well as tolerance concepts and demolding constraints. The 3D geometry is created in an optimization cycle and in parallel undergoes simulation runs to validate load cases with the geometry of the design. Cost checks also running in parallel with this guarantee the target cost being achieved.

The polyamide 66 Durethan AKV 50 H2.0 from Lanxess turned out to be ideal for the design of the lightweight carrier in the installation space available. This construction material satisfies not only the high demands relating to dynamic durability under the influence of heat but also the corresponding raw-material properties for cost-effective production.

During the development phase, the advantages of the plastic were rigorously exploited. This meant that a directly threaded connection was possible with the plastic. There was now no need for the cost-intensive metal inserts which would have had to be implemented in an additional process step. In collaboration with a specialist in plastic screws a solution was worked out which allowed the filter to cope with being fastened and unfastened more than 50 times, for example, following maintenance or replacement. The preloading forces of the screws in the carriers remain so high that the filter element cannot come undone by itself. In addition, sheet-metal holders were integrated in the design phase and injection-molded into the component directly. This also served to reduce material and installation costs.

For reasons of cost efficiency the injection-molding tool took the form of a family mold which enables a complete set of lightweight carriers to be produced with each shot. The very different weights of the two carriers call for a high degree of simulation skill during the tooling design. Near-net-shape cooling while using special heat-conducting sliding inserts makes economic cycle times possible.

Success was achieved in integrating the lightweight carrier into existing Actros production because, among other things, identical bushes were used for both holders, which meant that standard screws could still be used. These tried-and-tested screw systems could also be retained for fastening the fenders since inserted metal nuts were incorporated in the plastic holders.

The weight reduction achieved in the component itself is 54%. Further weight savings are achieved through the elimination of installation material such as angled plates, screws and nuts. The project shows that metal substitution projects are economically viable even in ongoing series production. The project goal of lower weight at a lower cost has been achieved.

Innovative plastic applications for a small urban bus concept

G. Kopp, **O. Deißer**,
DLR Institut für Fahrzeugkonzepte, Stuttgart;
A. Müller, **S. Beyer**, Hochschule Esslingen

Abstract

The ‘Reallabor Schorndorf (BOOLEAN)’ project, one of seven research projects which, funded by Baden-Württemberg Ministry of Science, Research and Art, test future-proof solutions for challenges in metropolitan areas. In real laboratories, scientists together with local authorities, businesses and citizens work on changes in the city.

Within the context of the project presented here, an innovative, lightweight, urban bus concept is developed which takes into consideration the special requirements for vehicle developments in public transport which will be necessary in the future. In a multi-stage process, sketches and rough drafts are developed first. These are used among other things in public participation in order to specify further requirements made of the vehicle. In a next step, the draft and vehicle architecture are implemented in a constructional design.

A particular challenge in this project is the inclusion of all involved parties in the conception and implementation of this innovative vehicle concept and its technical implementation in a vehicle model which addresses among other things the topics of environmental compatibility, safety and comfort.

These requirements are met in particular by a systematic comparison of the lightweighting potentials of selected modes of construction which include different polymer applications and sandwich structures.

In addition to the load-path-optimized frame structure, the main structural components of floor, roof and side walls are designed using different plastic and sandwich configurations (SMC, LFT, LFI, etc.) and their lightweighting potential compared.

Innovative lightweight design for light-duty commercial vehicles: the GRP leaf spring

Dr.-Ing. **J. Stimpfl**, Dr.-Ing. **J. Asbeck**,
Mubea Fahrwerksfedern GmbH, Attendorn

Abstract

The 100-year old owner-managed company Muhr und Bender KG (Mubea) in Attendorn is the world market leader in the development and manufacture of automotive components, such as axle springs, stabilizers, spring band clamps or valve springs. The company's success to date is also attributable to the early focus on lightweight construction in combination with a high degree of vertical integration from the raw material to the final product as well as to the internal development of production processes.

On the basis of the subsidiary company Mubea Carbo Tech GmbH’s manufacturing and product know-how relating to carbon-fiber-reinforced plastic (CFRP) automotive components, in combination with many years of experience working with the chassis, the Chassis Technologies division has been developing glass-fiber-reinforced plastic (GRP) suspension springs since 2008. One special milestone has been the first serial production of GRP longitudinal leaf springs for powered rear axles.

The Mubea GRP leaf tension spring is a special innovation in which not only is the steel replaced by the lightweight material GRP but also a new patented design suitable for fiber composites is used. With the aid of the leaf tension spring design it is for the first time possible to replace multi-leaf steel springs for light commercial vehicles with single-leaf GRP springs. The innovative design and the elimination of length compensation in the form of the shackle lead to an increasing overlay of the bending component with a tension component during compression. In this way a continuously progressive spring characteristic became possible for the first time despite a single-leaf spring design.

Mubea GRP leaf springs and leaf tension springs are produced in series quantities with the aid of the prepreg compression molding production technology. What is special here is the use of a ribbon-like prepreg (that is, pre-impregnated fibers). This gives a number of advantages with regard to the production process and the GRP spring product. Firstly, with continuous prepreg production all fibers in the spring are optimally impregnated and unidirectionally aligned. Secondly, the stretched and not laterally trimmed fibers adjust optimally to the contour during compression, despite variations in the thickness and width of the spring geometry. Furthermore, the chemical crosslinking of the plastic takes place entirely under

high pressure. During the cooling process, this prevents the formation of pores, micro-cracks or unevenness in the surface, due to material shrinkage or differences in strain.

All in all, Mubea GRP leaf springs offer not only a very high weight saving of as much as 50 kg per axle with lightweight construction costs appropriate for the market but also a significant increase in driving comfort.

Industry-driven initiative to standardize continuous-fiber-reinforced thermoplastics for use in the automotive industry

Dr.-Ing. **S. Schmeer**, Dr.-Ing. **D. Scheliga**,
Institut für Verbundwerkstoffe GmbH, Kaiserslautern

As is the case with other materials, the properties of continuous-fiber-reinforced thermoplastics are characterized in experimental investigations as well. Reference is made here in some cases to uniform standards but often also to different standards. To secure a good universal validity, latitude and room for interpretation are frequently left open in the details of the application. Particularly in the case of continuous-fiber-reinforced thermoplastics this leads to misinterpretations and thus to different characteristic values, also because the standards were often prepared for thermoset composite materials. In some areas of relevance, there may not be any standards or industry-specific standards at all. Against this background a transparent, consistent, and efficient strategy of characterization for describing continuous-fiber-reinforced thermoplastics (organo-sheets and tapes) is to be developed in the working group and then standardized. Here the focus in on material characterization, characteristic values for material comparisons, and also quality assurance concepts. In particular, the aim is to supply the users of materials with usable and sufficient material characteristic values for material simulation which go beyond the current level.

Fig. 33: Composition of the working group and of the accompanying OEM committee

This working group is headed by the IVW and under the umbrella of the AVK the following companies are participants: Arkema, BASF, Covestro, Dupont, DSM, Evonik, Lanxess/Bond Laminates, Sabic and Tencate. The solutions worked out are then closely discussed with an OEM committee in which the companies BMW, Daimler, Ford, Opel and the VW Group are represented.