

ATZ extra

October 2014



The Project **ThyssenKrupp** InCar plus

Solutions for Automotive Efficiency

INNOVATION

Dear Reader,

2009, the 111th year of the ATZ's existence, saw the publication of initial documentation on a company's internal research and development project: InCar. The reason for this was that ThyssenKrupp had not only developed and presented individual innovations but an entire raft of solutions at that time. The Group has now further extended this approach with InCar plus. Back in 2009, the focus was still clearly on the body and chassis areas. Today, the solutions developed in interdisciplinary and cross-business unit teams are spread evenly across three topic areas: powertrain, chassis and steering, as well as body. InCar plus therefore contains the Group's entire automotive know-how.

The express objective of this progression was to surpass the present state of the art in at least one of the criteria of sustainability, weight, economy and performance. The focus was placed on environmentally compatible solutions concerning energy efficiency, electric mobility and lightweight design. The supreme objective of all of these is to support vehicle manufacturers and achieve competitive advantages for them.

And what ThyssenKrupp has achieved in over 30 subprojects comprising more than 40 individual solutions is really very remarkable. Many of these reveal a very high level of maturity and can usually be easily integrated into production. In certain cases, ThyssenKrupp has also developed the corresponding manufacturing or assembly process for implementation in large-scale production.

However, the issue of responsibility is also very important, because a number of these solutions are able to improve environmental performance. This is not least because the Group has scrutinized the entire life cycle of the products and components rather than concentrating on partial areas.

This ATZextra will provide you with an insight into the results of what is the largest development project ever undertaken by a supplier without OEM involvement and, at the same time, the largest individual project ever undertaken by ThyssenKrupp. I hope you enjoy reading about these exciting developments.



DR. ALEXANDER HEINTZEL, Editor in Chief
Wiesbaden, September 12, 2014





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GENERAL NOTE:

All statements as to the properties or uses of materials or products are for descriptive purposes only. Calculations and technical assessments relate exclusively to the reference structure or the stated reference products and will require renewed investigation or express confirmation in concrete cases of use of the respective material or product. Guarantees in respect of specific properties or uses are only valid if agreed in writing.

OCTOBER 2014

The Project ThyssenKrupp InCar plus

InCar stands for ThyssenKrupp's automotive technology expertise. In 2009, the Group unveiled its developments in the three topic areas powertrain, chassis and steering, as well as body. The innovation program is being continued with the InCar plus project. It includes solutions which are close to or ready for volume production and which can quickly be integrated into ongoing projects.

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FOREWORD

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INCAR PLUS: HIGH LEVEL OF MATURITY FOR HIGH STANDARDS

The automotive sector is undergoing rapid transformation. Global competition, high rates of growth in many parts of the world and a sharp awareness of mobility which is as environmentally friendly as possible are driving this change. This is underpinned by circumstances such as demographic trends, progressive urbanization and climate change. These are resulting in both enormous challenges and significant opportunities for the automotive industry. As a diversified technology group and long-term partner to the automotive industry, we are involved in structuring this change process and are developing products and services that are meeting demand for “more” in a “better” way.

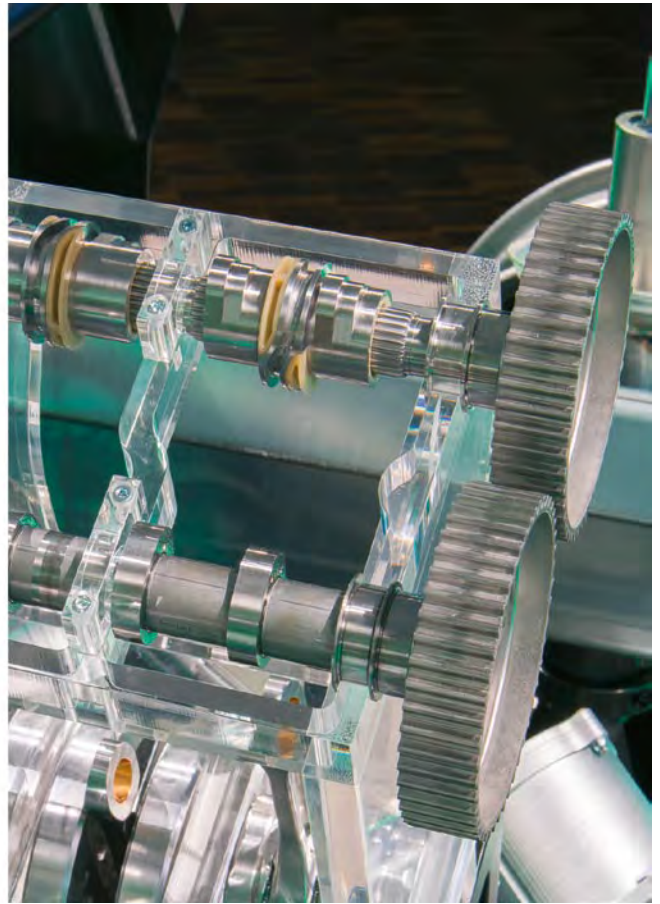
The automotive industry has been an important customer to ThyssenKrupp for many years. Around a quarter of our sales are generated in this sector. Today, we are one of the world's leading material and component suppliers to OEMs and are also an important development partner.

Under the motto “ThyssenKrupp InCar plus – Solutions for Automotive Efficiency”, we have implemented the largest development project ever undertaken by a supplier without OEM involvement. At the same time, InCar plus is currently the most extensive ThyssenKrupp research project of all time. In over 30 subprojects with more than 40 individual solutions, our engineers have developed new products in the areas of powertrain,

chassis and steering, as well as body. These are focused on environmentally compatible solutions concerning energy efficiency, electric mobility and lightweight design. Irrespective of whether weight, economy, sustainability or performance is concerned: each of our InCar plus innovations will surpass the present state of the art in at least one of these points.

The powertrain subproject is concentrating on the further development of the valve train. Our objective was to increase the efficiency of the combustion engine and significantly reduce fuel consumption and therefore emissions. One example of this is our innovative camshaft technology. We are able to reduce energy losses within the engine using alternative bearing concepts. The integration of further functions such as oil separation into the camshaft is giving our customers access to new options. This innovation therefore saves space and additionally reduces emissions. With our electric drive innovations, we are treading new ground in the field of electric mobility. High-strength electrical steel with its improved magnetic properties is of central importance in this regard, because it increases the efficiency of electric machines.

As material specialists, we have focused our attention on economic lightweight design in the body subproject. Thanks to the use of new grades of steel, innovative composite materials



The InCar plus R&D vehicle encompasses over 30 innovations from the powertrain, chassis and steering, as well as body segments

and modern processing methods such as hot-forming, we have succeeded in meeting our customers' increasing requirements on lightweight design, economy and safety with new products. This applies to both classic structural components such as the longitudinal member or B-pillar and closures as well as add-on parts such as the hood or doors. We have also included body-based topics such as seats or wheels in the developments and have achieved excellent results in terms of economy and weight reduction with high-strength steels.

The chassis and steering subproject is focused primarily on the further development of electronic steering systems. Electric power steering is the ticket into the world of partially or fully autonomous driving and goes hand-in-hand with a significant reduction in fuel consumption in comparison with conventional hydraulic steering systems. Our InCar plus innovations help to use these steering systems even more efficiently and make them available to new vehicle classes. The multi-material design of damper tubes and steering components is a further development focus. We have also developed corresponding manufacturing and assembly processes for implementation in large-scale production.

ThyssenKrupp InCar plus bundles the Group's entire automotive know-how. The Components Technology, Industrial

Solutions and Steel Europe business areas have integrated their expertise. The result is innovations that have been tested and validated along the entire value chain. This includes material forming and machining steps, tool and prototype construction as well as joining and assembly technology for large-scale production. This interdisciplinary approach has led to unique results. Numerous InCar plus solutions can significantly improve the ecological life cycle assessment, for instance. This encompasses all phases of a product's life – from raw material extraction and processing, to material production and component manufacturing, to end product usage and recycling. One further advantage for our customers is comprehensive validation of these new developments. Our objective is the smoothest possible integration of our components into volume production. To ensure this, we have done the groundwork and have developed tools, built prototypes and conducted a variety of tests. The result is the extremely high level of maturity of almost all of the InCar plus solutions developed for our demanding customers in the automotive sector.

Discover our automotive expertise for yourself. We hope you enjoy reading about the many exciting developments within the InCar plus project.

INCAR PLUS: SOLUTIONS FOR AUTOMOTIVE EFFICIENCY

InCar stands for ThyssenKrupp's automotive technology expertise. In the three topic areas powertrain, chassis and steering, as well as body, the Group is developing solutions which are close to or ready for volume production and which can quickly be integrated into ongoing projects. The objective is to support vehicle manufacturers and achieve competitive advantages for them.

The results of the first InCar project were presented in 2009. The project was a complete success, especially for customers, who were able to benefit in the long term from the broad range of automotive innovations. The innovation program for the automotive industry is being continued with the InCar plus project. ThyssenKrupp is developing new products in the areas of powertrain, chassis and steering, as well as body in more than 30 projects with over 40 individual solutions, ❶. The motto is: solutions for automotive efficiency.



LIGHTWEIGHT

Efficiency Means Making Future Vehicles Even Lighter.

New steel materials and semi-finished products, composite materials, magnesium, carbon fiber reinforced plastics (CFRP) or aluminum are making significant contributions to lightweight material design. Material-friendly design and innovative structures are bringing this potential to fruition. New manufacturing and joining technologies are being developed on the basis of ThyssenKrupp's engineering and material expertise. Development is focusing on the simple integration of innovative InCar plus solutions into production at the OEMs.

InCar plus solutions are characterized by their high level of maturity and

extensive economic and manufacturing technology validation. The basis of this is the ThyssenKrupp Group's expertise as a material and component manufacturer and a tool and manufacturing technology partner.

Example of carbon fiber reinforced plastics: with the ThyssenKrupp Carbon Composites Competence Center, ThyssenKrupp has founded a new company primarily involved in investigating economic, large-scale production of CFRP components. New, innovative developments have been transferred to standard products in cooperation with ThyssenKrupp System Engineering and the component experts at ThyssenKrupp Presta.

For example, the Group's bundled expertise was used to design new, super lightweight steering columns. The weight of individual components can be reduced by up to 60 % through the use of CFRP in steering columns which are fit for production.



COST-COMPETITIVE

Efficiency Means Making Future Vehicles Even More Cost-competitive.

Future vehicles must also remain affordable – despite the constant increase in safety requirements, comfort and functional improvements. Intelligent steel lightweight design plays a key role in this:

ThyssenKrupp Steel Europe is developing ultra high-strength steel materials to meet the ever increasing lightweight and safety requirements of modern vehicle bodies. They enable significant weight reductions to be achieved while at the same time being highly cost-competitive.

Their processing in large-scale production necessitates a material-friendly component design. This starts with component conception and design and extends from structural mechanical validation to joining and forming technology aspects. This is where ThyssenKrupp System Engineering's expertise comes into play – up to and including tools and prototypes for innovative components. ThyssenKrupp is therefore bundling the Group's entire automotive know-how to offer OEMs the best solution.



HIGH-PERFORMING

Efficiency Means Further Increasing the Performance of Future Vehicles.

Innovative damping systems by ThyssenKrupp Bilstein increase ride comfort and safety. The new generation of electric steering systems, up to and including steer-by-wire, will make a contribution towards increasing comfort and safety. Not least because they support driver assistance systems which offer end customers genuine added value.



Efficiency Means Making Future Vehicles Even Greener.

The sustainability performance of vehicles is becoming an increasingly important competitive factor in the automotive industry. ThyssenKrupp believes that sustainability is driving innovation and attaches particular importance to environmentally friendly and recyclable materials, components and systems.

Innovative camshaft technology solutions are contributing to optimization of the combustion engine. The ThyssenKrupp Camshafts group is focusing on lightweight design and friction reduction to sustainably reduce fuel consumption and thus CO₂ emissions in vehicle operation.

While current legislation concentrates on emissions during vehicle operation, it disregards emissions caused during material and component manufacturing as well as recyclability at the end of the product life cycle. In contrast, ThyssenKrupp addresses the entire life cycle.

The ecological life cycle assessments for InCar plus solutions disclose the emissions for all phases of a product's life – from raw material extraction and processing, to material production and component manufacturing, to end product usage and recycling.

Such an approach is important in material selection, for example. Steel lightweight design concepts enable environmental impacts to be improved throughout the entire life cycle. Although alternative materials may reduce emissions during the driving

phase in many cases, the production phase has such an impact on the environment that it can be only partially compensated for during the use phase.

All InCar plus solutions deliver a significant advantage in at least one efficiency aspect in comparison with the current state of the art. Many solutions have been developed to production maturity and extensively tested in hardware, with the result that the innovations can be quickly integrated into current projects and developments. In future topics such as steer-by-wire, ThyssenKrupp is positioning itself as an innovative development partner. The development work is consistently oriented towards the OEMs' objectives: for increased efficiency and long-term competitive advantages.

Powertrain

- Friction-optimized camshaft
- Oil separation system POSS®
- Hybrid shiftable cam element
- Hybrid cylinder head cover module
- Exhaust system
- High-strength electrical steel
- Acoustically optimized electric motor
- Assembled rotor
- Assembled gear shaft eTDC
- Electrified rear axle
- Fuel cell

Chassis & Steering

- ThermoTecWire® springs
- Function-optimized damper tubes
- Integrated variable damping system
- CFRP lightweight steering column
- Hybrid steering shaft
- Hollow steering rack
- Superimposing actuator
- Column EPS for compact class
- Steer-by-wire system

Body

- Reference structure update
- Cockpit beam
- Bumper systems
- Longitudinal member
- A-pillar
- B-pillars
- Tailored Tempering technology
- LITECOR® potential analysis
- Hoods
- Door
- Seat structures
- Wheels



POWER



EFFICIENT

TRAIN



Increased efficiency, fewer emissions: this is the simple foundation on which ThyssenKrupp's objectives for the InCarplus powertrain subproject are based. Further development of the valve train is the focal point for the combustion engine, e.g. in the form of innovative camshaft technologies and alternative bearing concepts to reduce friction losses within the engine. The integration of additional functions such as oil separation into the camshaft is opening up new options for the automotive industry. With a number of innovations relating to the electric drive system, ThyssenKrupp is also tackling this important future topic. With its improved magnetic properties, high-strength electrical steel is of central importance to electric mobility: it increases the efficiency of electric motors.



NEW IDEAS FOR MORE ECONOMIC ENGINES

In addition to efficiency gains through downsizing, turbocharging and direct injection, the detailed optimization of all engine components is making an important contribution towards economic and low-emission combustion engines. Friction losses in the engine are particularly important. In the InCarplus project, this is addressed through optimized valve train solutions. Additional potential is being tapped through lightweight solutions with innovative material combinations and functional integration.

REDUCED FRICTION IN CAMSHAFTS

More than ever before, constantly increasing requirements on the combustion engine are making it necessary to reduce its friction losses. Valve train friction amounts to around 15 % of total engine friction. Economically interesting potential for a significant reduction exists here. ThyssenKrupp has systematically studied new approaches based on further developed manufacturing and coating processes on the cams and the camshaft bearings. In the future, specially developed test rigs will enable a quick, objective comparison for various engine types.

Camshafts usually have two areas of contact with their environment which are susceptible to friction: the camshaft bearings and the cams. Friction can be reduced at both contacts by specifically machining the ground, standard surface.

Cam friction contact is preferably optimized if this involves sliding contact – e.g. bucket tappets. Coating this contact partner, especially with layers consisting of amorphous carbon (diamond like carbon, DLC) is state of the

art. Additionally coating the cams promises further tribological advantages but necessitates coating a ground camshaft which is ready to install and masking those surfaces which are not to be coated. So far, this laborious and expensive process has prevented cam surface coating in large numbers in consideration of the cost-benefit ratio anticipated on the market.

ThyssenKrupp has further developed its assembly technology so that pre-

ground cams which are coated prior to assembly can now also be joined using the standard press- and form-fit process. This includes 100-% in-line quality control of the joint as a unique characteristic. Cost-effective manufacturing of a DLC-coated camshaft is now possible thanks to these innovations, ❶. Initial studies show that this coating reduces friction torque by around 30 % over wide speed ranges.

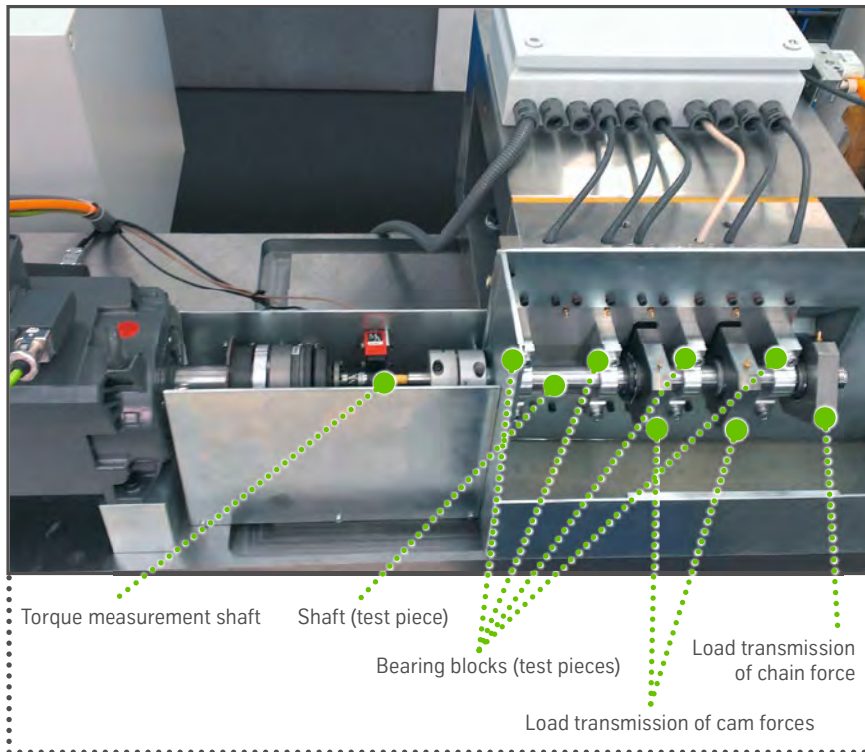
CAMSHAFT BEARINGS – HYBRIDIZATION REQUIRES IMPROVED SOLUTIONS

Nowadays, camshafts are typically using hydrodynamic plain bearings lubricated with pressurized oil. In this case, a steel camshaft with a ground surface rotates in split aluminum bearings. These are typically machined in a complex line boring process. The camshaft is then mounted in the journal bore. The engine oil is pumped into the journal through a pressure oil bore counter to the cam force vector, is carried along by the rotating shaft and thereby separates the friction partners.

InCar® plus solution



❶ Friction-optimized camshaft with DLC-coated cams



② Laboratory test rig for friction loss measurement on camshafts

A mixed friction range in which the shaft and the bearing bore come into direct contact is transited during engine start-up. As the relative speed between the shaft and bearing bore increases, the hydrodynamic contact ratio increases until it completely separates the two friction partners. According to the studies conducted so far, this point typically lies slightly above idle speed. Engines with start-stop system pass this starting procedure significantly more often than engines without this technology. Consequently, they operate in the

unfavorable mixed friction status for longer.

In addition, resulting frictional heat which is incurred has to be dissipated from the bearing area via the oil and the components. This is valid whether classic, split camshaft bearings or non-split camshaft bearings are used. The non-split bearings can be used in modules in which an assembled camshaft is joined in an enclosed supporting frame or in the cylinder head cover.

The objective of this investigation is to optimize individual tribological system

parameters and to develop a measurement methodology which ensures sufficient measurement quality and comparability, etc. The focus is placed on the bearing geometry and surface, the material combination and the effective bearing load. Other influencing variables such as the lubricant, temperature or relative movement are regarded as invariable.

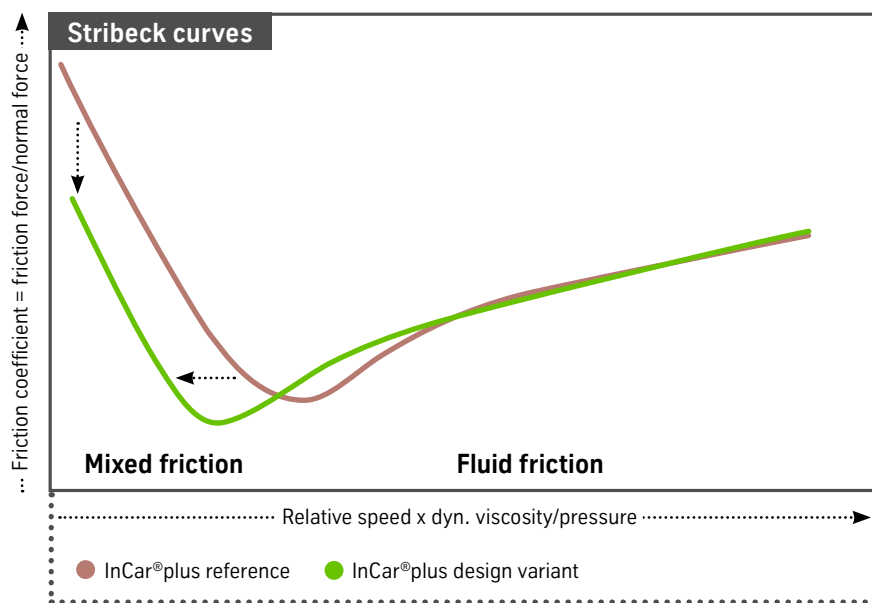
There is already a range of publications concerning approaches for improving the tribological system. Some of these concern design details and some involve commercial market solutions such as coatings or heat treatments. Solutions in the research stage are also dealt with but are analyzed less intensively due to their lack of implementation maturity. Often, however, the solution approaches are not technically or commercially comparable, as the developments are based on different engines. ThyssenKrupp has therefore developed a friction measurement test rig which is independent of the engine design type but which can be adapted to the engine-specific loads and enables comparable statements, ②.

COMPARATIVE FRICTION ANALYSIS THROUGH IMPROVED TEST TECHNOLOGY

The system to be tested consists of a camshaft tube without cams and four bearing blocks. An electric motor drives the shaft; a measuring shaft acquires drag torque data. The normal forces are not generated through the valve train and its drive, as in real engine operation, but are integrated by two piezo actuators. These simulate the dynamic

Shaft	Bearing block										
	Gray cast iron	Sintered steel	Die-cast aluminum part (basis)								Basis, changed bearing geometry II
			Basis, unchanged	Sliding lacquer	Aluminum coating with micro-porosity	Press-fitted ceramic bushes	Press-fitted PTFE bushes	Roller bearing	Integrated cast iron rings	Basis, changed bearing geometry I	
Ground	●	●	●	●	●	●	●		●	●	●
Tungsten sulfide			●								
DLC			●								
Nitrided	●	●	●								
Bearing material								●			

③ Selection of investigated design variants



④ Objective of surface machining (schematic representation)

cam forces. In addition, a pneumatic cylinder simulates the pre-load force of the drive chain or belt, which is assumed to be constant. A shaft bending line which is approximately that of a camshaft in the cylinder head is achieved by the specific arrangement of these actuators. The test rig control system also enables adaptation of the force signal depending on the rotational speed and thus the simulation of realistic speed curves. Testing down to standstill is possible; engine starting and ramp-up from standstill can be simulated. The oil can also be pre-conditioned, allowing the pressure at the bearing points to be adapted to the operating situation. Various heating elements and thermal insulation measures control the test pieces' temperature and simulate the engine's operating conditions. In all, these measures create constant boundary conditions for comparable tests.

Due to the small measuring range, concentration on the analyzed friction contact and the avoidance of dynamic excitation from the valve train through the omission of the friction partners in the cylinder head (cups or roller actuation), this test rig can also measure small torque differences of up to 0.006 Nm. As the test pieces are built in reduced form and therefore inexpensively for the test runs, ThyssenKrupp can test an extensive matrix, including repeat tests, at very low cost. ③ shows the variants tested in the first test series.

LESS FRICTION THROUGH APPROPRIATE ALTERNATIVES

The reference used for the test rig investigations is a ground shaft which alternatively runs in plain bearings manufactured from cast aluminum alloys or in needle bearings. Both bearing variants are established production solutions, and the shaft complies with the conventional production specifications.

In deviation from this, ThyssenKrupp is studying further bearing materials. Bearing blocks manufactured from a sintered material developed for plain bearings as well as gray cast iron bearing blocks are used, for example. Surface structure and property modifications are also investigated, e.g. using conventional market solutions such as coatings with sliding lacquer or DLC, nitriding, or ceramic or PTFE bushings. These are complemented by new approaches such as changing the bearing macro-geometry, treatment with tungsten sulfide integrated into the surface cavities and the application of a microporous layer of aluminum.

The objective of these surface treatments and rig tests can be outlined on the basis of a sketched Stribeck curve, ④. Firstly, the friction coefficient in the mixed friction area should decline. Surface optimization is aimed at achieving different effects in this case. For example, shearing-off of bonds in direct body contact can be facilitated or the plastic deformation of roughnesses can be

reduced through a changed surface structure. Increasing the hardness of the surface and therefore reducing abrasive grooving is also worth considering.

Secondly, ThyssenKrupp also wants to shift the disengagement point, at which the switch from mixed friction to fluid friction takes place, towards lower rotational speeds. This occurs with a smoother surface structure. In simple terms, contact between material tips is to be prevented at lower rotational speeds. One other approach is to increase surfaces' oil affinity. Possible modification processes use one or more of these mechanisms.

OUTLOOK

A flexible tool is now available in the form of the test technology and system which has been developed for measuring friction losses at camshaft bearings. It enables systematic investigation of the approaches potentially suitable for reducing friction with repeatable test parameters. These advanced tests are not only intended to determine the greatest possible potential for reducing friction but also identify solutions offering the best cost-benefit ratio. Particularly promising solutions will subsequently be studied and evaluated in greater detail in motored cylinder head tests. Transferring the developed solutions to camshafts for commercial vehicles will also be considered.

CAMSHAFT-INTEGRATED OIL SEPARATION SYSTEM

ThyssenKrupp has succeeded in integrating the oil separation system for blow-by gas, as part of the crankcase ventilation system, into a camshaft. Despite its low package requirements, the technology, called the Presta Oil Separation System (POSS), surpasses the separation performance of the majority of current passive oil separation systems in covers or bolted onto the crankcase. It therefore makes a significant contribution towards meeting future emissions requirements and reducing the engine package. This is already being demonstrated through a first application in production.

The separation of oil from the blow-by gas is becoming an increasingly important part of the crankcase ventilation system in combustion engines. This is because, firstly, downsizing measures are impacting on the quantity and aerosol composition of the blow-by gas and secondly, tighter emissions legislation is raising the requirements on oil separation systems.

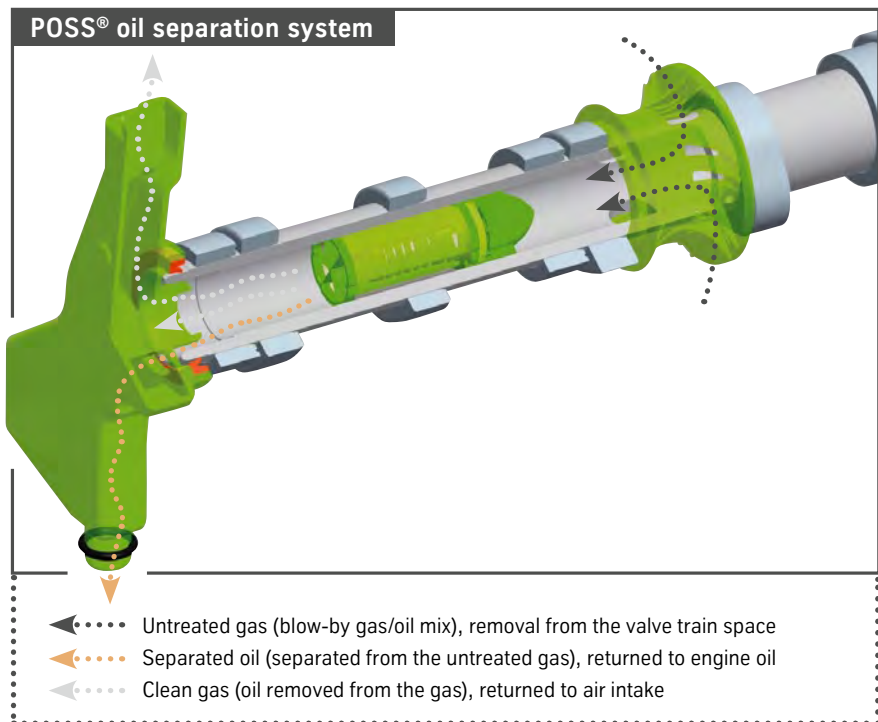
In the combustion process, blow-by gas escapes from the combustion chamber due to the design-related gap between the piston (rings) and cylinder wall and enters the crankcase or the valve chamber along the valve stem seals respectively. Among other substances, it contains engine oil, fuel residues and condensate in the form of aerosols. This gas mixture has to be transported away from the crankcase in a controlled manner and returned in a closed-loop circuit to the air intake and therefore the combustion process.

So that combustion engines can be further optimized and still meet the increasing emissions requirements, aerosol constituents have to be removed from the blow-by gas more effectively prior to combustion. Oil separators with additional engine package requirements are state of the art. They are either bolted onto the crankcase as an external module or are part of the cylinder

head cover. Hybridization, exhaust gas recirculation systems, pedestrian impact protection and lightweight design are necessitating increasingly compact engines. Increasing value is

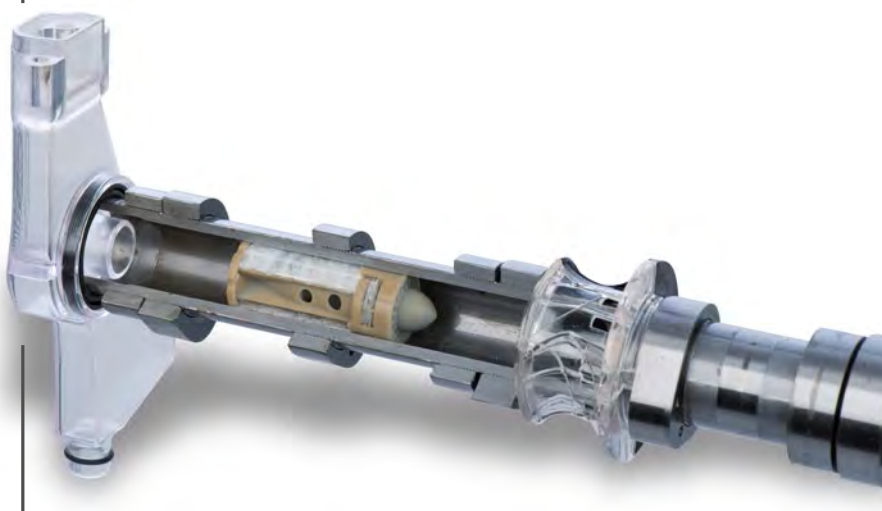
being placed on function and component integration. POSS makes a convincing contribution to this, ❶.

Unlike cast or forged variants, assembled camshafts use a hollow tube shaft.

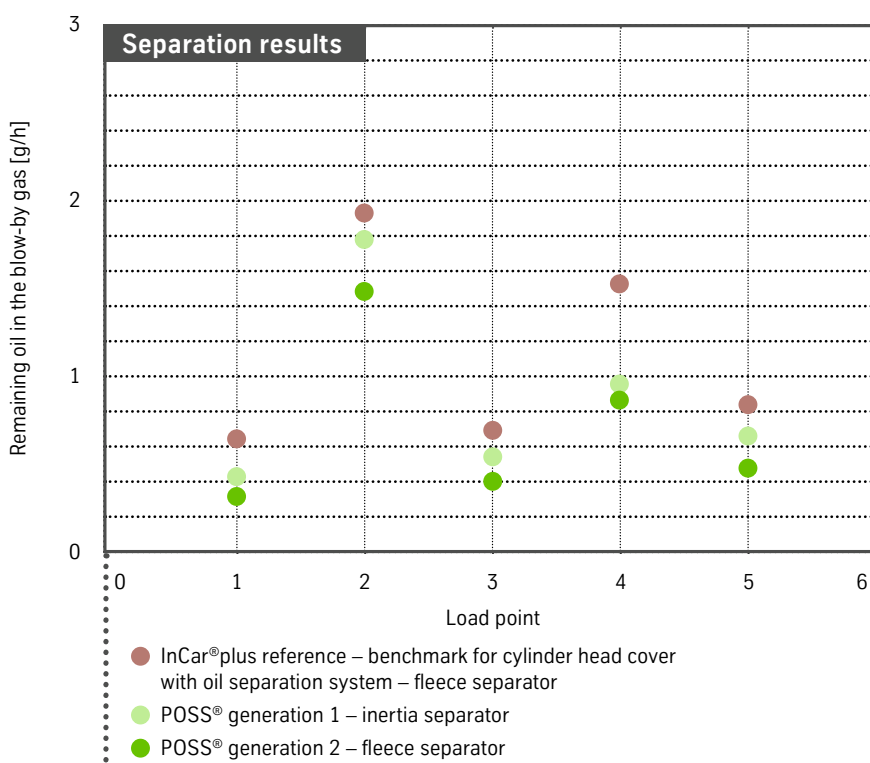


❶ POSS functional principle in the camshaft

Sectional model



② Sectional model of the oil separation system integrated into the camshaft



③ Remaining oil in the cleaned blow-by gas for various oil separation systems

This offers space for integrating additional functions, such as oil separation, ②.

TAILORED FUNCTIONAL DEVELOPMENT

ThyssenKrupp has developed the oil separation system as part of InCar plus. The

result is a system which integrates the functions of untreated gas removal, oil separation plus clean gas and oil transport into the camshaft and the valve train. The separation results not only surpass the systems on the market in terms of essential performance characteristics. POSS additionally offers a clear package

advantage. For example, the oil remaining in the cleaned blow-by gas is reduced by 30 to 50 % depending on mode, ③.

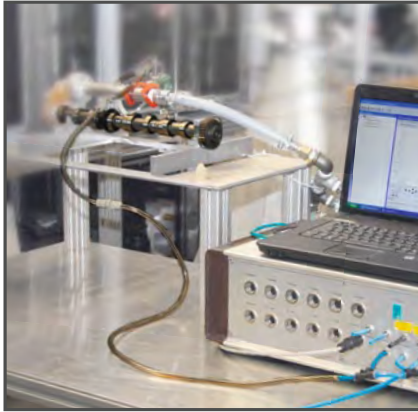
The blow-by gas conducted into the valve chamber within the engine enters the camshaft through radial holes. The gas inlet is protected by a splash guard mounted on the camshaft. It keeps splash oil and coarse oil drops generated in the valve chamber away from the gas inlet. Influences caused by oiling neighboring valve train components must be taken into consideration in the design.

Inside the hollow camshaft, the untreated gas passes through the actual oil separator. The POSS system developed in the InCar plus project offers extensive potential here through the combination of inertial separation with fleece materials. This configuration additionally offers blocking and diffusion effects which support the separation of minute particles even at low flow velocities.

Being maintenance-free over their entire service lives is a central requirement of oil separation systems. The combined inertia-fleece separator meets this requirement unreservedly; no exchange or maintenance intervals are planned. In contrast to the usual filtration principle of through flow, the gas merely flows against the fleece. The separator is designed so that crankcase ventilation is ensured even if the surface of the fleece possibly becomes clogged.

Design variants which separate the oil from the gas using the inertial, blocking or diffusion effect are possible depending on application requirement. Supported by the centrifugal forces of the rotating camshaft, the oil separated from the aerosol is transported away to the end of the shaft as a film on the inner wall of the tube. A clean gas duct, which is sealed by a low-friction radial shaft seal, is flange-mounted there. The separated oil is prevented from being carried along by the specific design of the clean gas duct's cross-section and the resulting changed gas velocities up to an engine- and mode-dependent limit value.

The design of the oil separator is based on measurements on an engine test rig. The reference in this case is the blow-by untreated gas spectrum (composition of the untreated gas) of a modern, turbo-charged 2.0-l diesel engine. The analysis of the untreated gas spectrum shows



④ Laboratory test rig for determining the fraction and overall separation level as well as pressure loss

that the engine forms a high number of particles smaller than $1\ \mu\text{m}$ under full load, something which is typical of highly turbocharged engine concepts. These small particles, however, make up a high percentage of the total weight of the untreated gas spectrum.

Additional requirements on system development arose due to pressure pulsation tolerability and a maximum pressure loss of 10 mbar at a volumetric flow of 60 l/min. This occurs at an operating point with high load at a low engine speed. In this case, the turbocharger only generates a low vacuum, but a high blow-by volumetric flow occurs at the same time.

EXTENSIVE ANALYSIS AND VALIDATION

The important result variables for assessing the efficiency of a separation system

are the fraction separation level and the overall separation level with reference to the overall system's pressure loss. The optimization loops for verifying the design variants are undertaken on the laboratory test rig shown in ④.

The removal of separated oil is being intensively investigated on a further laboratory test rig developed specifically for this project. It is used to visualize the oil drain behavior with a transparent camshaft dummy and different transparent variants of the clean gas duct. Particular attention is paid to critical flow areas, such as the clean gas duct and camshaft tube interface, the internal geometry of the duct and the oil drain.

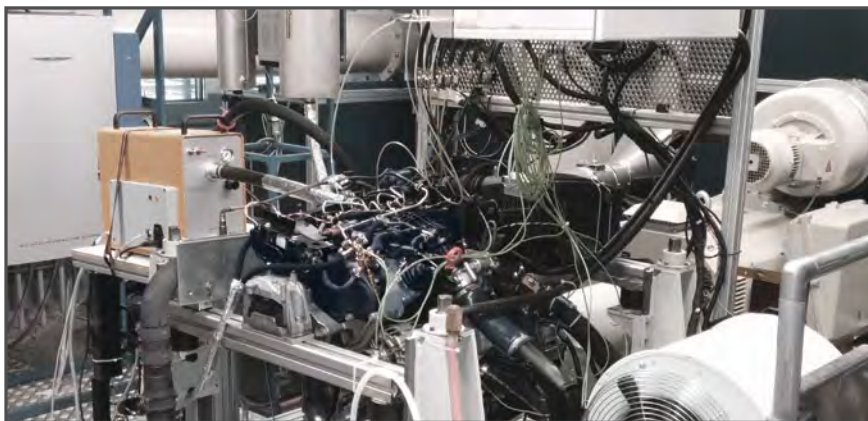
In addition to the investigations on the laboratory test rig, an extensive test program is undertaken on an engine test rig, ⑤. Here, comprehensive test series are performed on a specially converted test engine and the oil drain behavior,

the durability of the system and its long-term stability are analyzed, for example.

This test rig setup also enables stress tests according to OEM specifications and determination of the system limits. One of these “limit tests” investigates the volumetric flow as of which oil is carried along from the valve chamber and into the separation system, thus overloading the system. Specific design measures and parallel validation on the laboratory test rig are implemented to achieve the volumetric flow target value of 200 l/min defined for the test engine despite smaller cross-sections. Possible sooting or soiling of the fleece is investigated in long-term tests. It demonstrates that the separation performance does not deteriorate towards the end of the test and that pressure loss across the overall system does not increase.

OUTLOOK

Integration of the oil separation system into a camshaft offers OEMs increased engine architecture design freedom. A follow-on project is dealing with simplified integration into existing engine concepts, the possibility of combination with variable valve train systems instead of conventional, hollow camshafts and also further improvement of the function. This involves further development in the form of a non-rotating system which is controlled irrespective of volumetric flow. Initial prototypes have already undergone successful testing on a component test rig.



⑤ System testing on the motored engine test rig

HYBRID SHIFTABLE CAM ELEMENTS IMPROVE VALVE LIFT SWITCHING SYSTEMS

ThyssenKrupp has developed a lightweight shiftable cam element for variable valve lift systems. Thanks to its hybrid design, this is up to 30 % lighter than a reference component cut from solid steel. This weight advantage enables the valve lift switching speed limit to be increased, resulting in a potential fuel saving of up to 5 %. The newly developed hybrid design economically and innovatively joins steel components together using a plastic injection molding process.

As they can be extensively implemented with zero package impact compared to conventional valve trains, valve lift switching systems based on axially movable shiftable cam elements have attracted interest since their market launch a few years ago. With its product, process and material know-how, ThyssenKrupp has studied the optimization potential of shiftable camshafts as the key factor of such variable valve lift switching systems and has driven their implementation forward. Two-stage switching systems are state of the art. The second cam profile is often used for cylinder deactivation.

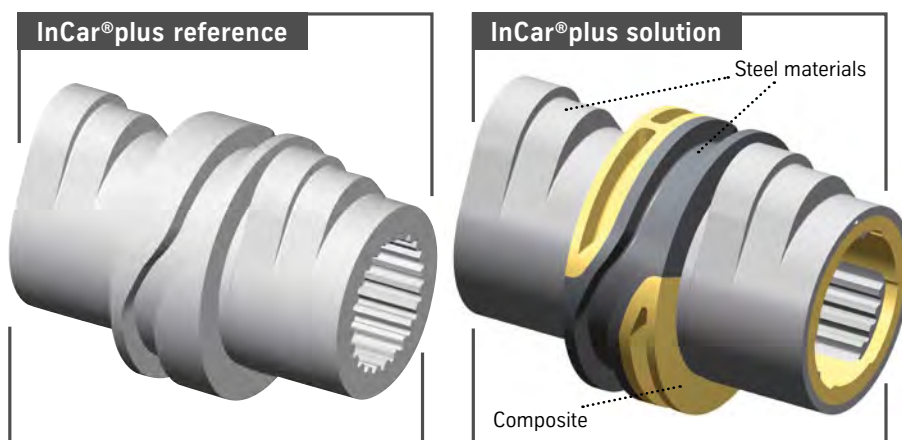
The increase in downsizing and the related increase in mean pressures are resulting in the necessity of a three-stage changeover system. Subdivision of the map into three valve lift ranges causes the changeover points to shift to higher speeds, but higher speeds and masses place greater strain on the control grooves and the actuator than before. However, the mechanical resilience of both components limits the permissible shifting speed. This conflict cannot be resolved e.g. by redesigning the control grooves. The significantly limited package in this area extensively restricts design freedom.

THE SOLUTION IS LESS MASS

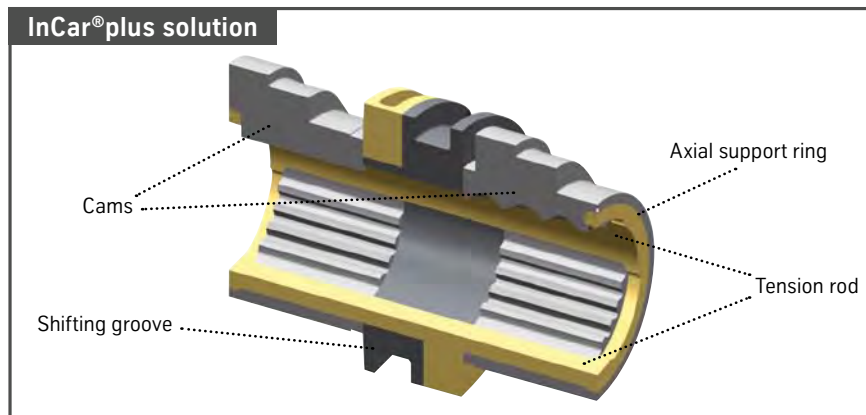
In contrast, reducing the mass on the shiftable element appears to be a plausible approach to implementing a three-stage shiftable cam system, ❶. It also offers the opportunity of an independent design approach in addition to the existing patents registered for such valve lift switching systems.

A stress-optimized combination of steel components with a high-perfor-

mance plastic ensures this weight reduction on the shiftable cam element, ❷. Axial cohesion between the cams and the gear shifting gate is ensured by three plastic tension rods and axial support rings at the ends of the shiftable cam element consisting of a fiber reinforced, thermally stabilized plastic. Manufactured from 31CrMoV9, the weight-optimized gear shifting gate is encapsulated in plastic. In consideration of the resulting 20 % reduction in operating load and



❶ Three-stage shiftable cam element in monolithic (left) and hybrid design (right)



② Sectional view of the hybrid shifttable cam element

the required levels of safety, its wall thicknesses can be minimized. Recesses in the cams offer the clearance required for the tension rods and support rings. The plastic surrounding the gear shifting gate also radially reinforces the tension rods.

The hybrid design offers a further advantage as regards the choice of material. The individual components can be manufactured separately, thus allowing different materials to be selected for the steel components and individual heat treatments to be performed. The component can therefore be optimally adapted to the stress.

INNOVATIVE MATERIAL AND PRODUCTION CONCEPT

The positive and frictional cohesion between the control groove and cams is

generated in the injection molding process. Extensive mold flow simulations were undertaken to develop the tool concept required for this. This led to the achievement of a homogeneous material structure appropriate to the stress in all areas filled with plastic, ③.

Depending on the stresses which are encountered, carbon or glass fiber reinforced plastics are used; these offer a significant weight reduction of up to 30 % and thus considerably lower loads during the shifting process.

The hybrid shifttable element is designed for a maximum nominal shifting speed of 4000 rpm and 4×10^6 load cycles. An overspeed limit of 5000 rpm is defined. The resulting stresses were determined in a multi-body simulation. Among other aspects, this gives consideration to the influences of detent and frictional forces as well as play in the

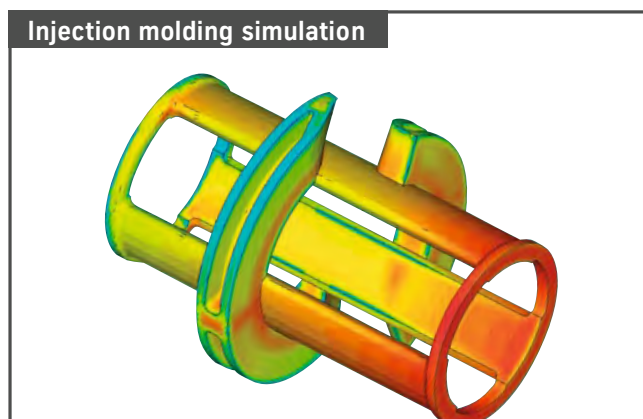
system. The determined stresses form the basis for a detailed FEM evaluation.

The axial acceleration forces are supported via the axial support ring and the plastic elements surrounding the gear shifting gate in interaction with the tension rods. In this constellation, the maximum stresses occur in the relevant transitional areas, ④. However, specific design and smooth cross-section transitions in these areas guarantee the required component safety.

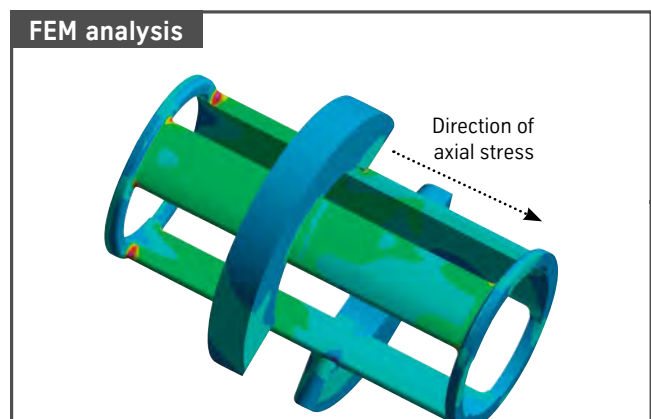
A special test rig was designed for initial mechanical testing of the hybrid shifttable element. The frictional forces acting in the valve train are taken into consideration through the integration of valve play compensation and the roller cam followers into the design. Validation of the mechanical durability for the required number of load cycles in technical tests is undertaken in a specially thermally conditioned environment. In parallel, the real accelerations which occur are determined using a laser measurement process and the simulation model is validated.

OUTLOOK

Initial mechanical testing under exposure to the real stresses took place on a component test rig and confirmed the lightweight potential of 30 %. Defined, permissible actuator pin stress in the reference component enables the shifting limit speed to be increased by 1000 rpm. ThyssenKrupp will undertake cycle-related tests to validate the statements concerning the level of further fuel reductions, using motored engine tests.



③ Plastic composite mold flow simulation



④ Resulting stresses in the FEM analysis

CAMSHAFT MODULES – OPTIMIZATION THROUGH HYBRID DESIGN

The development of cylinder head cover modules with integrated, assembled camshafts led to significant weight, friction and cost advantages. With a hybrid material approach consisting of plastic, aluminum and steel components, ThyssenKrupp is showing how weight can be reduced by a further 15 %. Hybrid camshaft bearings consisting of aluminum bearing brackets with cast-in bearing rings reduce friction loss by around 10 to 15 W and the volume of oil required in the plain bearings by 30 to 40 %.

Since the market launch of cylinder head cover modules with integrated, assembled camshafts in 2011, the classic split plain camshaft bearings have been revolutionized and extended by a modular approach for diesel and gasoline engines.

Since then, camshafts can be assembled in monolithic aluminum cylinder head covers or ladder-type frames to form modules which are ready to install. Significant weight reductions have already been achieved here. Measures for reducing friction, such as smaller bearing diameters, enclosed plain bearings or the use of roller bearings have also been implemented. The manufacturing costs are considerably lower due to the omission of seals and fasteners. In particular,

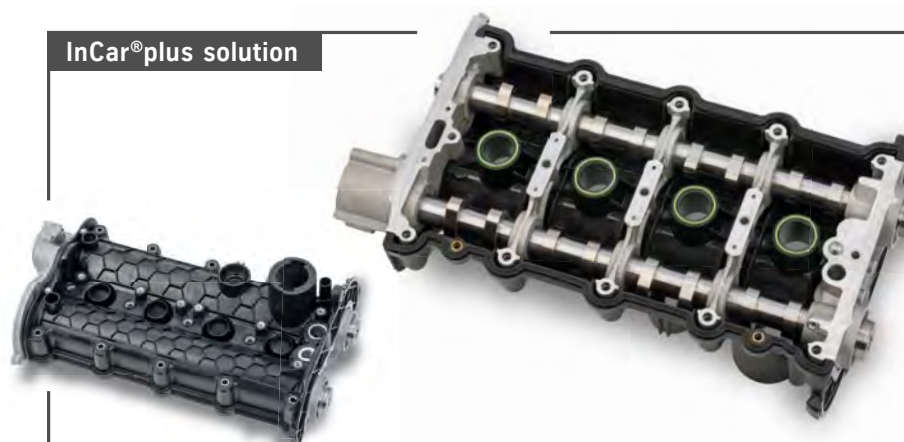
the design with a ladder-type frame and separate, mounted plastic cover also achieved positive acoustic effects.

What is common to all camshaft modules so far is the fact that the steel shaft's plain bearing is mounted in an aluminum bearing bore. As temperatures of -40 to 150 °C can occur in the area of the camshaft bearings during engine operation, the different thermal expansion coefficients of aluminum and steel lead to the enlargement of the bearing gap as the engine temperature increases. At the same time, the engine oil's viscosity decreases as it heats up. This results in increased oil flow rate through the bearing gap; this has to be compensated by the oil pump to the detriment of engine efficiency.

The hybrid camshaft module designed by ThyssenKrupp, ❶, combines the advantages of the monolithic cylinder head cover and ladder-type frame design. In this case, hybrid refers to the ready-to-install module using main components consisting of different materials. The main components are aluminum bearing brackets with a function-optimizing core, ❷, and the plastic cover. All components are optimized in consideration of the material and stress.

BEARING BRACKETS WITH FUNCTION-OPTIMIZING CORE

In comparison with monolithic aluminum cylinder head covers, individual bearing brackets offer lightweight design potential thanks to fewer geometry



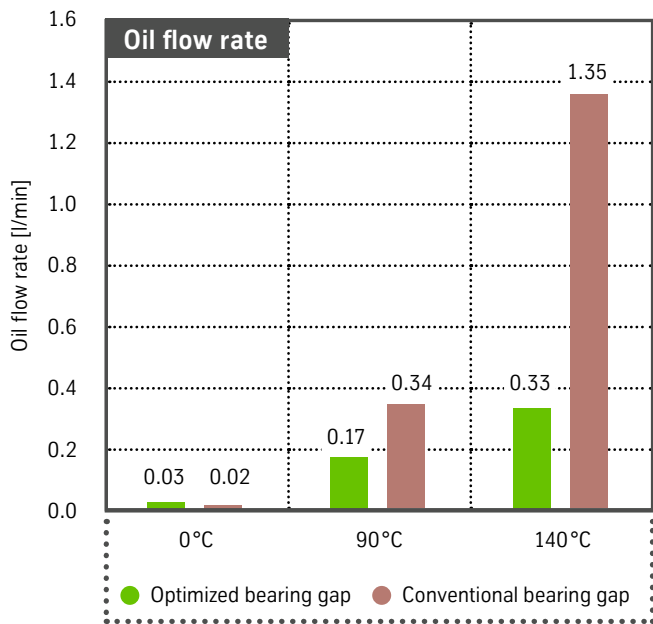
❶ Hybrid camshaft module



❷ Bearing bracket with function-optimizing core

Material	Density	Thermal expansion coefficient
Aluminum	2.70 g/cm ³	23.1·10 ⁻⁶ K ⁻¹
Steel	7.81 g/cm ³	11.8·10 ⁻⁶ K ⁻¹
Sintered steel	5.00 g/cm ³	11.8·10 ⁻⁶ K ⁻¹
Composite (60 % AlSi ₉ Cu ₃ , 40 % Al ₂ O ₃)	3.21 g/cm ³	12.9-14.3·10 ⁻⁶ K ⁻¹

③ Comparison of densities and thermal expansion coefficients



④ Oil flow rate with conventional and optimized bearing gap

restrictions in the casting process. This is because they can be designed more specifically for the direction of the timing assembly and valve train forces which occur. The considerably simpler design of the bearing brackets facilitates their further optimization. For example, material accumulations which are required to cast a monolithic aluminum cover but which are not necessary in functional terms can be avoided. Material cross-sections can be reduced in those areas not relevant to function or strength. The monolithic cover's extraction direction does not permit any undercuts for reducing material.

Bearing brackets with a function-optimizing core are cast aluminum parts with partial bearing inserts consisting of porous materials based on ceramic or ferrous materials. These harmonize the thermal expansion of camshaft generals with the camshaft, ③.

Micro-geometric, positive connections were developed with ceramic and sintered materials in the die-casting process and new infiltration processes were also analyzed. While extreme lightweight design is possible with the ceramic material, the sintered metal ring is a cost-efficient production solution which can be implemented quickly. Macro-geometric, positive connections were also achieved with stabilizer rings consisting of ferrous material completely encased in aluminum.

In all bearing brackets with a function-optimizing core, the camshaft is mounted in the aluminum and the reinforcement ring, whose thermal expansion coefficient is equivalent to that of the camshaft, keeps the bearing play at an approximately constant level across all temperature ranges. FEM analyses prove that the stresses occurring in the

bearing bracket in all temperature ranges are not critical. ④ shows the simulated reduction of oil flow rate. Besides reducing the oil flow rate at the bearing points, additional measures are to be implemented to further reduce friction losses at the camshaft. Possible solutions which can be combined are being developed in the "Reduced Friction in Camshafts" project, as these can also be used for individual camshafts (see article from page 13).

PLASTIC COVER WITHOUT ADDITIONAL ASSEMBLY EFFORT

The plastic cover is the second main component of the hybrid camshaft module. It fulfills the following functions, which are to be taken into account in component design and material selection:

- : sealing to the cylinder head and environment using an acrylate rubber seal
- : orientation of the bearing brackets in the module and positioning of the module on the cylinder head using a tolerance-balanced assembly process
- : mounting of add-on parts with the aid of cast-in threaded bushings
- : integration of fasteners and caps in the cover geometry.

In geometric terms, the plastic cover developed during the project is based on the reference cylinder head cover and is therefore an alternative with virtually zero package impact in comparison with the current technology. Due to the significantly lower specific weight of the plastic, the new cover with bearing brackets is around 500 g lighter than the monolithic aluminum reference cover. Only minor changes to the cover geometry are



⑤ Continuous elastomer seal

Temperature [°C]	Steel camshaft	Aluminum bearing block	Δ Bearing play	Hybrid bearing block with Fe reinforcement ring	Δ Bearing play	Optimization of bearing play
-40	-18 μm	-36 μm	-18 μm	-33 μm	-15 μm	3 μm ► Potential reduction in minimal play
150	37 μm	66 μm	+29 μm	53 μm	+16 μm	13 μm ► Reduction in temperature-dependent increase in bearing play

6 Bearing gap depending on engine operating temperature

necessary to guarantee high dimensional stability. To ensure the required temperature and media resistance as well as processing capability in the injection molding process, PA66 GF35 was selected as the material; it is used in diverse ways as the standard polymer for applications in the combustion engine.

A continuous elastomer seal seals the plastic cover to the bearing brackets and the cylinder head. At the same time, the seal decouples the cover from the engine's vibration acceleration, 5.

ThyssenKrupp has developed a new process to join the main bearing bracket and plastic cover components. It not only means that the engine manufacturer no longer has to assemble the plastic cover but also reduces the machining effort in comparison with monolithic aluminum covers. Bushings pressed into the bearing brackets form a frictional and positive connection with the plastic cover. These bushings are joined to the plastic cover using the newly developed thermal process.

EXTENSIVE VIRTUAL AND REAL VALIDATION

In parallel with development, analytical and numerical calculations are used to validate the design of the main components. Forces and torques from the valve train were taken into consideration in the FE analyses. The elastomer seal forces acting on the bearing brackets were also analyzed while designing the connection between the camshaft module and plastic cover. The main stresses in the plastic calculated in a FEM analysis are a maximum of 10 % of the permissible values in the area of the con-

nection between the plastic cover and the camshaft module.

A further FEM calculation analyzed bearing gap formation at operating temperatures from -40 to 150 °C. The bearing diameter for an aluminum bearing block and a hybrid bearing block with reinforcement rings manufactured from ferrous material was calculated, taking the threaded connection into account. 6 shows example changes in diameter at temperatures of -40 and 150 °C for the steel camshaft, the aluminum and the hybrid bearing blocks. It can be seen that the hybrid bearing block's reinforcement ring

reduces both aluminum shrinkage and expansion.

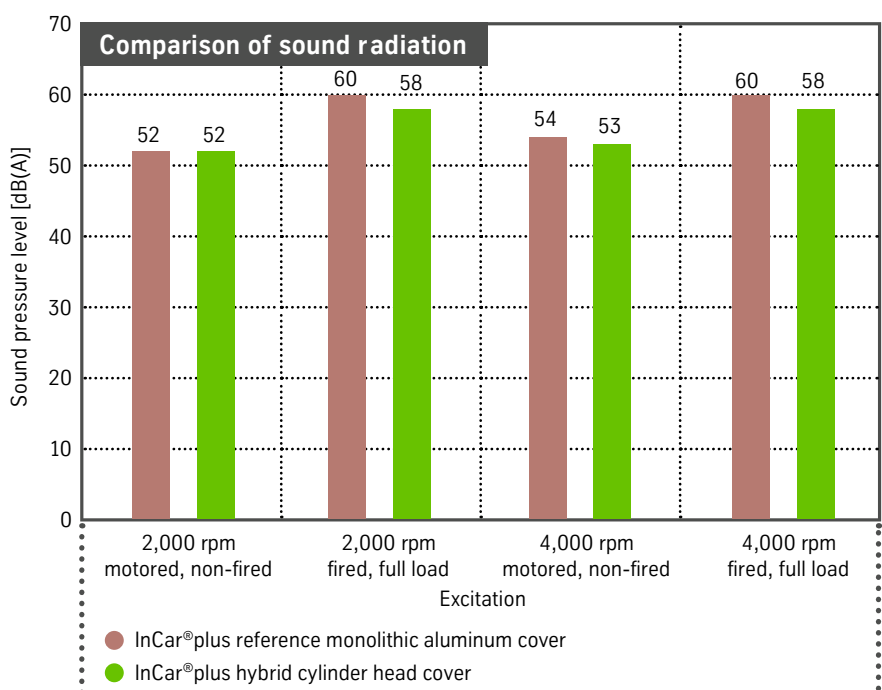
Preliminary tests show that oil consumption can be reduced by 30 to 40 % by harmonizing the thermal expansion coefficient of the camshaft and bearings. ThyssenKrupp is currently verifying the calculation results on a motored cylinder head test rig.

A validation program consisting of modal analysis, strength tests, temperature cycle tests to age the plastic, leak tests and acoustic tests is used to validate the function of the plastic cover.

Acoustic decoupling, structural optimization and the good self-damping properties of the plastic enable sound radiation to be reduced in comparison with the monolithic reference cover, 7.

OUTLOOK

The project shows that cylinder head cover modules with integrated, assembled camshafts can be further improved. Even today, additional potential for function integration can be seen; this is being investigated conceptually using the example of actuators for variable valve trains, non-rotating blow-by-gas oil separators or vacuum pumps. New approaches dealing with weight reduction are also undergoing testing.



7 Reduction of sound radiation through the plastic cover

HEAT-RESISTANT, DENSITY-REDUCED STEELS FOR EXHAUST SYSTEMS

Due to their chemical composition, heat-resistant, density-reduced steels reveal particularly favorable characteristics for exhaust systems. While development of these materials has not yet been completed, an advantageous characteristics profile is nevertheless becoming apparent. In addition to high strength at low and high temperatures and high corrosion resistance, their low thermal conductivity and low density are particularly remarkable.

Since the early 1970s, exhaust systems have been manufactured from ferritic stainless steels. However, the introduction of exhaust gas treatment, more stringent emissions standards and changes in customer requirements are increasingly necessitating lightweight designs which not only reduce fuel consumption and emissions but also have a long life and are visually appealing. The ferritic chromium steel 1.4509 (X2CrTiNb18) commonly used for this application at present is characterized by its very high scale resistance and heat resistance. It is used as the reference in this development project. In particular, even higher heat resistance and improved hot gas corrosion resistance are two important requirements on the materials of future exhaust systems.

ThyssenKrupp is now focusing on an interesting material development with promising intermediate results. These indicate, that this heat-resistant flat steel offers positive characteristics such as high strength at low and high temperatures, the required high corrosion resistance and low thermal conductivity. It achieves all of this with a comparatively low density (around 8 % less than stainless steels), which predestines it as a material for lightweight components.

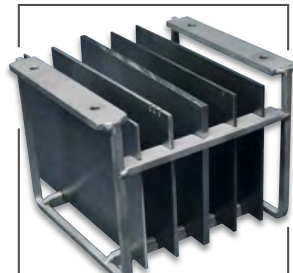
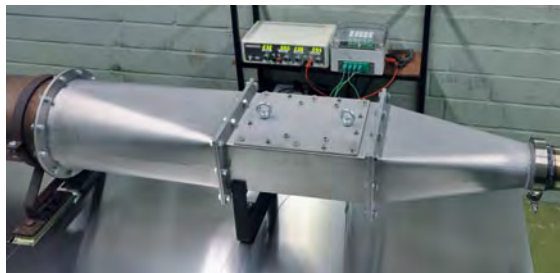
Due to the prototype character of the new material, ThyssenKrupp has so far produced individual coils in a semi-industrial process. Due to the special

chemical composition, material-specific manufacturing parameters have so far been derived and implemented with the aid of simulation techniques. The tested manufacturing process is being further optimized under technological and economic aspects. Due to low alloying costs and optimizable component geometries, potential savings are anticipated on use of the new material.

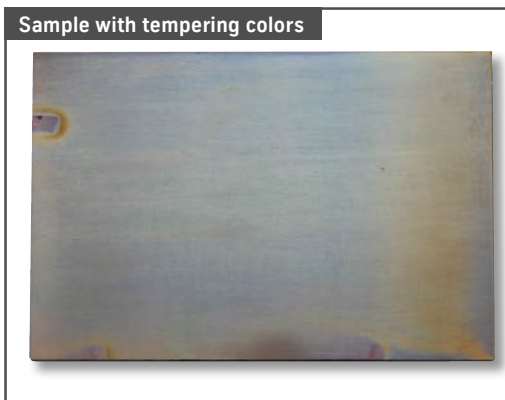
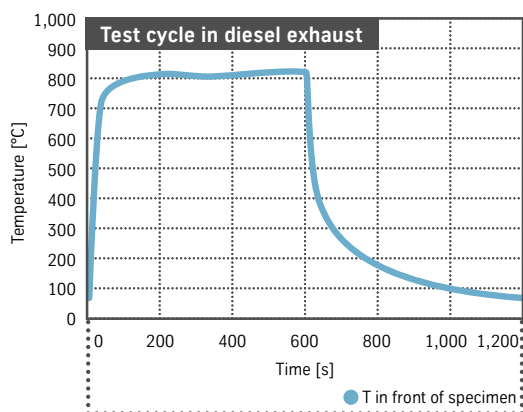
In an extensive study program, ThyssenKrupp has tested the new material's relevant processing and usage characteristics at room temperature and at maximum operating temperatures. The test environment was an exhaust gas chamber with real diesel exhaust gases under thermal loads alternating between room temperature and 800 °C, ❶. Visually, only slight oxidation limited to tempering colors is immediately noticeable, ❷. In comparison with the

significantly thicker, gray scale layer of the reference material under the same test conditions, the new steel's minor discoloration bears witness to its very high hot gas oxidation resistance.

Further fundamental cyclical oxidation investigations show that the new material also reveals high corrosion resistance in other aggressive substances. For example, only thin, slowly spreading layers of oxide can be ascertained at a temperature of 900 °C in moist air. This very high oxidation resistance prolongs the service life of the exhaust system and ensures a better visual appearance. In contrast, the chromium steel 1.4509 reference material reveals an oxide layer which increases around four times faster (weight increase) in the oxidation test and has a tendency to delaminate (weight decrease), ❸. A metallic surface



❶ Hot gas corrosion behavior test in the diesel exhaust gas chamber (left) and holder for the material specimens (right)



② Test cycle in diesel exhaust gas (left) and tempering colors after the cyclical endurance test (right)

exposed in this way continues to oxidize at increased speed when subjected to continued stress.

In addition to the material investigations, ThyssenKrupp has also used the material to manufacture selected prototype components for a diesel engine exhaust system and has tested these under full load/no load cycles, ④. In comparison with an exhaust system consisting of the reference material, the components manufactured from the new material reveal significantly lower external surface temperatures with the same wall thickness. This is attributed to the developed material's significantly lower thermal conductivity, which is around 40 % less than that of the reference material at room temperature.

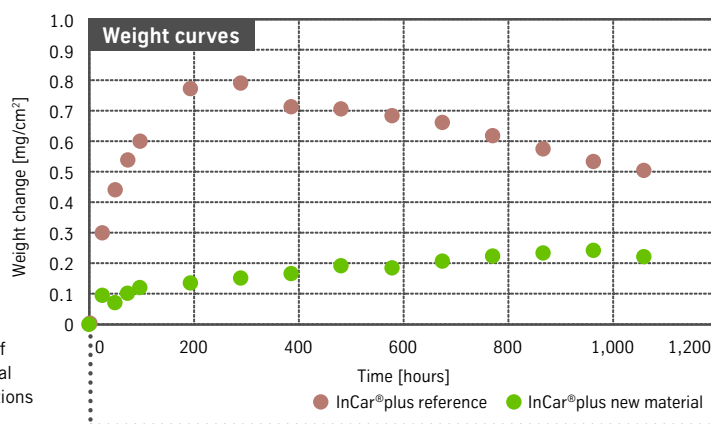
This reduced thermal conductivity leads to reduced heat escaping from the exhaust system, thereby enabling the catalytic converter and particulate filter to engage earlier. As a result, important emissions potential can be achieved with little effort. At the same time, exhaust tract cooling during engine standstill phases is slowed down, necessitating fewer secondary measures (e.g. insulation and shielding).

Other characteristics of this new material which are relevant to OEMs are comparable with those of the reference material. These include, for example, strength in a broad temperature range between room temperature and 900 °C. Extensive, detailed investigations on the topic of forming and joining behavior are currently in progress. Their objective is to be able to use the material in established production processes at exhaust system

manufacturers without extensive process adaptations. The approximately 8 % lower density of the new steel reduces the weight of the exhaust system and therefore makes an important contribution towards reducing fuel consumption and emissions.

Semi-industrial production of the material and initial, fundamental prototype part tests have confirmed its basic production capability plus attractive processing and usage characteristics.

Based on these intermediate results, ThyssenKrupp will undertake further development to access the potential which is undoubtedly available for production application. Further possible automotive applications are also being investigated in addition to the primarily analyzed use in the exhaust system. The material can also potentially be used outside of the automotive sector, e.g. in pipeline and plant engineering applications.



③ Weight curves of fundamental cyclical oxidation investigations in moist air



④ The prototype intermediate pipe (left) and muffler components for cyclical full load/no load tests (right)

A close-up, artistic shot of a car's instrument cluster. The background is dark, and the focus is on a green digital display. The display shows a large plus sign (+) in the center, composed of many small dots. Below the plus sign, the word 'EFFICIENCY' is written in a similar dotted font. The display is set against a dark background with some blurred light patterns, suggesting a high-tech, modern vehicle interior.

INTERDISCIPLINARY EXPERTISE IS OPTIMIZING ELECTRIC DRIVES

As pure electric traction motors or in hybridized powertrain configurations, electrified drives significantly help to achieve future emissions targets. Electric motors suitable for automotive use must therefore be further optimized in terms of their core efficiency and power-to-weight ratio characteristics in order to increase the drives' ranges. ThyssenKrupp is developing new, innovative solutions through the interdisciplinary cooperation of various product areas combined with extensive materials technology expertise.

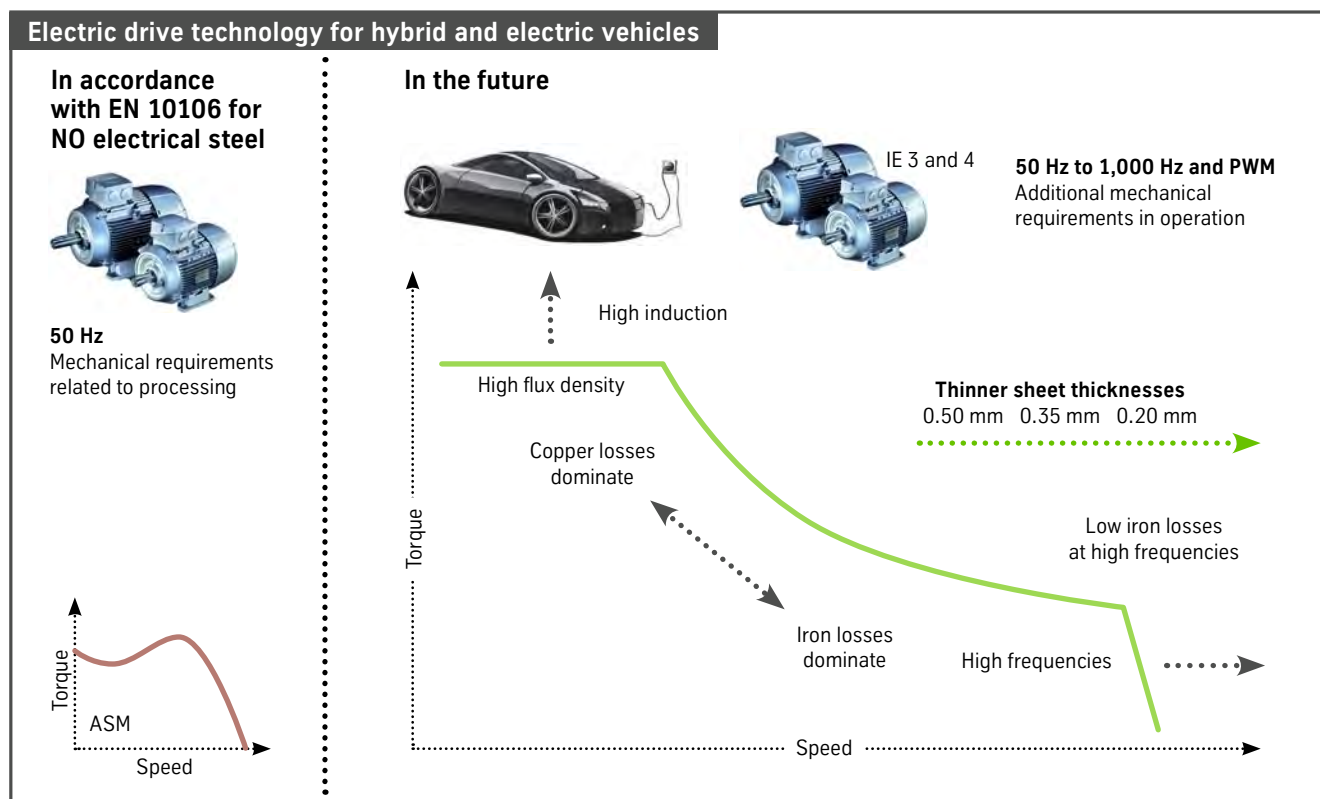
HIGH-STRENGTH, NON-GRAIN-ORIENTED ELECTRICAL STEEL

Drive motors for hybrid and electric vehicles must reveal maximum efficiency, low weight and an optimal package. This results in even higher requirements on the non-grain-oriented electrical steel. To meet these, ThyssenKrupp has developed new electrical steel grades which can be used to significantly increase the electric machine's torque in comparison with the best standard grade M 235-35 A. These grades also reveal magnetic guarantees for higher frequencies of, for example, 400 Hz with a guaranteed yield strength of over 420 MPa at the same time.

Electric motors with increasingly higher rotational speed and further increases in torque are the answer to passenger car trends such as energy and resource efficiency as well as weight reduction.

Demands on future electrical steel grades, ❶, are getting higher. ThyssenKrupp has long since embraced these demands and is developing prototypes with electrical steel grades for

drive motors for the InCar plus project. The electrical steel grade 280-30 AP, for example, is characterized by low losses at high frequencies and low deterioration of the soft magnetic characteristics in



❶ Current requirements on non-grain-oriented electrical steel (NO) according to the EN 10106 standard (left) and future requirements (right)

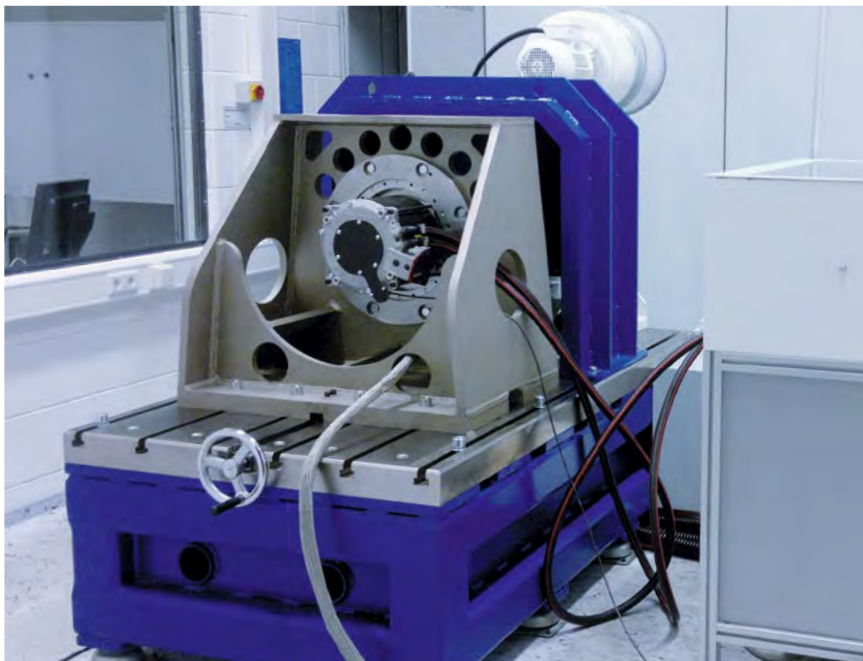
	In accordance with EN 10303	Standard grades in accordance with EN 10106			
Grade	NO 20	M 235-35 A	M 250-35 A	M 270-35 A	M 330-35 A
Rated thickness [mm]	0.2	0.35	0.35	0.35	0.35
P 1.0 50 Hz [W/kg]	0.9	1.0	1.0	1.0	1.2
P 1.5 50 Hz [W/kg]	2.4	2.3	2.4	2.4	2.7
P 1.0 400 Hz [W/kg]	11.7	16.6	18.6	18.4	20.9
P 1.0 1,000 Hz [W/kg]	43.0	70.0	82.0	80.0	91.0
R _{p0.2} typical [MPa]	360	425	370	360	330
R _{p0.2} guaranteed [MPa]	On request	≥ 360 resp. 390	≥ 350	≥ 350	≥ 320
R _m [MPa]	450	525	480	500	450
HV5	190	220	200	200	165

	Application-specific grades		High-strength grades			Extra high-strength grades
Grade	330-30 AP	270-27 AP*	280-30 AP	260-27 AP*	xxx-35 AP*	550Y40-35 HS**
Rated thickness [mm]	0.30	0.27	0.30	0.27	0.35	0.35
P 1.0 50Hz [W/kg]	1.2	1.1	1.1	1.1	1.1	On request
P 1.5 50Hz [W/kg]	2.8	2.6	2.5	2.4	3.0	On request
P 1.0 400Hz [W/kg]	18.0	15.0	16.0	15.0	22.0	< 40
P 1.0 1,000Hz [W/kg]	75.0	59.0	62.0	57.0	80.0	On request
R _{p0.2} typical [MPa]	330	390	440	430	450	520-620**
R _{p0.2} guaranteed [MPa]	≥ 300	≥ 350	≥ 420	On request	≥ 420	≥ 520**
R _m [MPa]	450	510	550	530	560	670-800**
HV5	168	180	200	200	200	200

Typical values for standard grades and indicative values for application-specific grades. Mechanical characteristic values measured at room temperature (RT) in rolling direction.

* New tests ** Various grades in development

② Comparison of relevant non-grain-oriented grades for use in a passenger car traction motor (* and ** designate grades in the test stage or of which only small quantities have been manufactured thus far, for which reason their values may fluctuate more extensively)



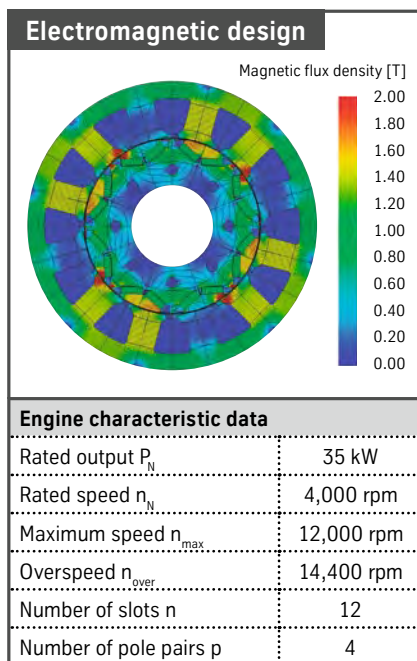
③ Motor test rig in the new E-Mobility Center Drives at ThyssenKrupp in Bochum

the rotor and stator manufacturing process.

ThyssenKrupp used various development approaches for new non-grain-oriented (NO) electrical steel grades. These new materials are characterized by guaranteed soft magnetic and mechanical properties. Electrical steel grades which are already used in traction drives today as well as new applications-specific grades were available for designing the electric motors, ②.

NEW TEST CENTER FOR ELECTRIC MOTORS

As part of the InCar plus project, three different prototypes of the electric motors were built and tested at the E-Mobility Center Drives at ThyssenKrupp in Bochum to validate the newly developed electrical steel grades. This development center has been supporting the applica-



④ Key data of the three synchronous machines

tion-specific further development of non-grain-oriented electrical steel since 2013; from FEM simulation and characterization of the soft magnetic and mechanical material properties, to validation on modern test rigs. A modern CO₂ laser cutting system is available for cutting motor laminations. The core element of

the development center is an electric machine test rig suitable for automotive use with a power rating of 140 kW at a torque of 230 Nm. The load machine of the test rig has a maximum speed of 18,000 rpm, ③.

COMPARISON OF THREE MOTOR CONFIGURATIONS

The three permanent magnet synchronous motors reveal key data in accordance with ④ and consist of stators manufactured from 280-30 AP electrical steel grade. The advantages of this material include low change in soft magnetic characteristics in the manufacturing process and low eddy current losses at high frequencies. The rotors consist of the non-grain-oriented electrical steel grades M 235-35 A, xxx-35 AP and 550Y40-35 HS, each of which reveals a different guaranteed yield strength.

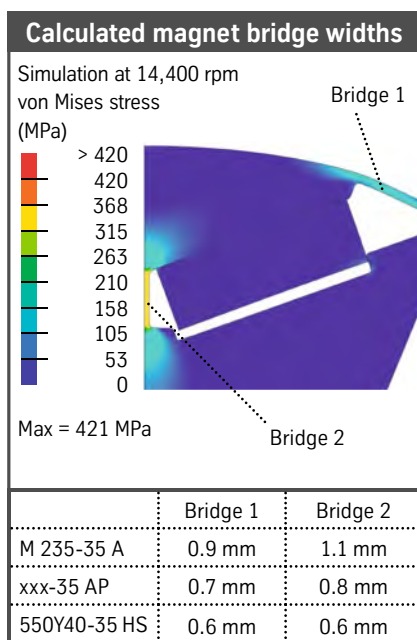
During development, particular attention is paid to the design of the magnet bridge widths in the prototype rotors, ⑤. The left part of the figure shows the mechanical simulation of grade xxx-35 AP. The bridge is selected such that the von Mises stress in the magnet bridge remains below the guaranteed material's yield strength at the overspeed of 14,400 rpm.

This results in the three different rotor geometries, ⑤ (left). Magnet bridge widths of 1.1 and 0.9 mm arise for the best, standardized grade M 235-35 A with typical losses of 16.6 W/kg and a guaranteed yield strength of 360 MPa. With the high-strength electrical steel xxx-35 AP, these can be reduced to 0.8 and 0.7 mm, and even to 0.6 mm with the extra high-strength electrical steel 550Y40-35 HS.

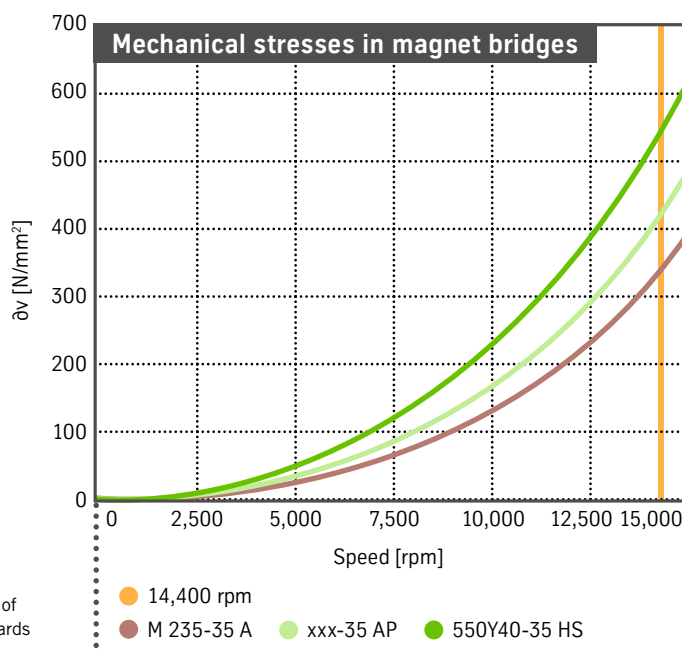
HIGH-STRENGTH ELECTRICAL STEEL IS THE BEST MATERIAL ALTERNATIVE

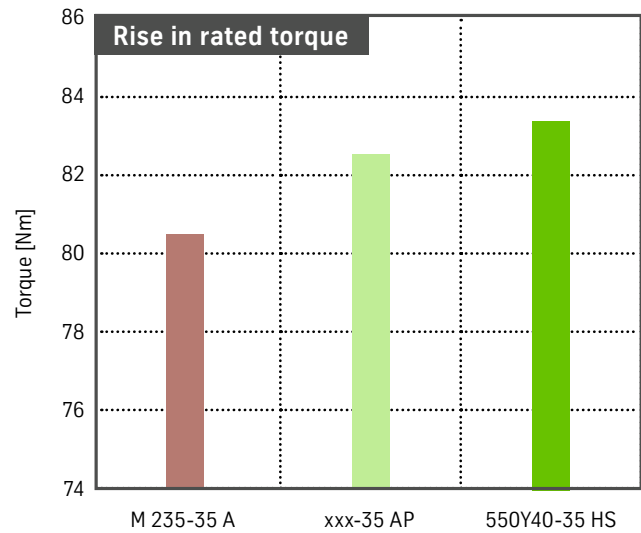
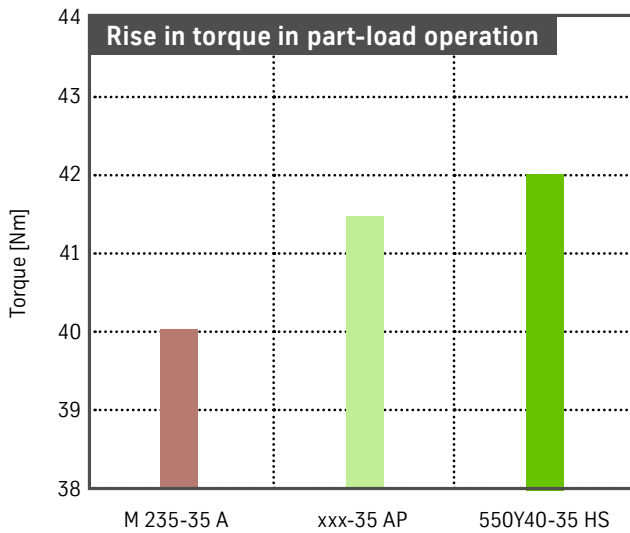
This design offers customers a number of advantages. For example, the rated torque is increased in the simulation through the use of the high-strength material xxx-35 AP with the same current intensity in comparison with the best standard grade M 235-35 A. Use of extra high-strength electrical steel 550Y40-35 HS results in a further increase in torque, ⑥. These simulation results are obtained with both an identical core length and an identical permanent magnet material mass.

The lower magnet bridge widths in the rotor reduce magnetic leakage flux, leading to the desired torque increase. This leads to better exploitation of the permanent magnets and further advan-

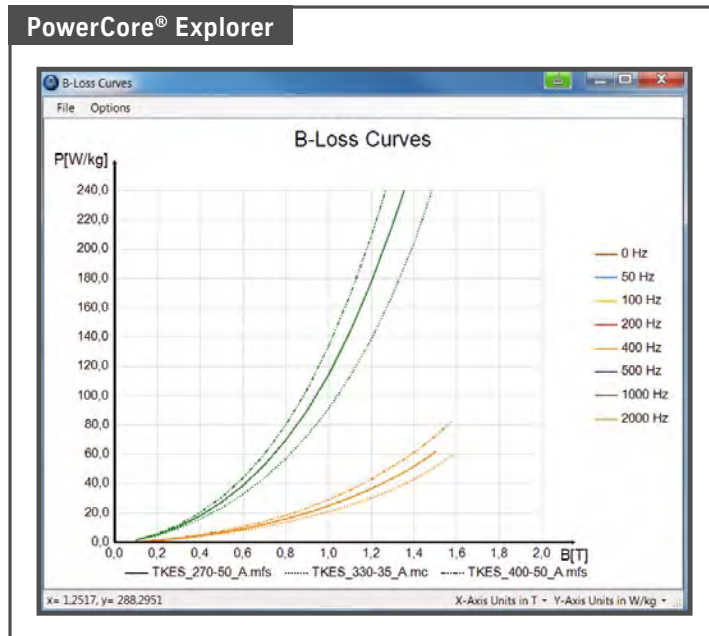


⑤ Mechanical design of the three rotors as regards the magnet bridges





6 Simulation results for the nominal speed of 4000 rpm



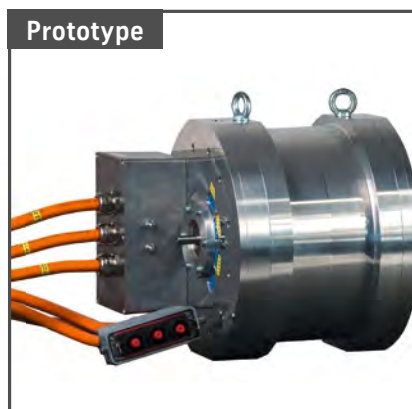
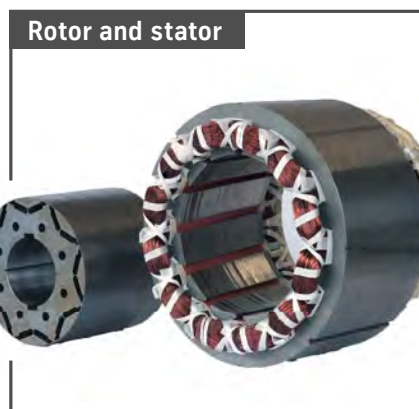
7 Powercore Explorer screen shot

tages for motor optimization. Less permanent magnet material can be used with an identical core length, or comparable motor performance can be achieved with a reduced overall length. While this requires redesigning the electric machine, it also offers further advantages in terms of costs, weight, package and energy. The torque increase approach is pursued in InCar plus.

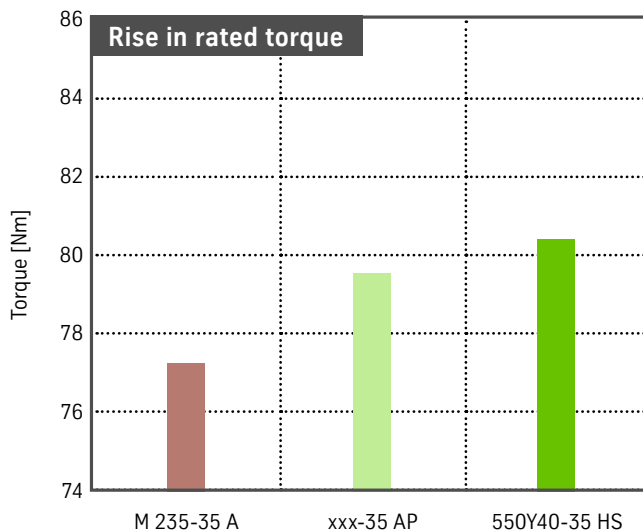
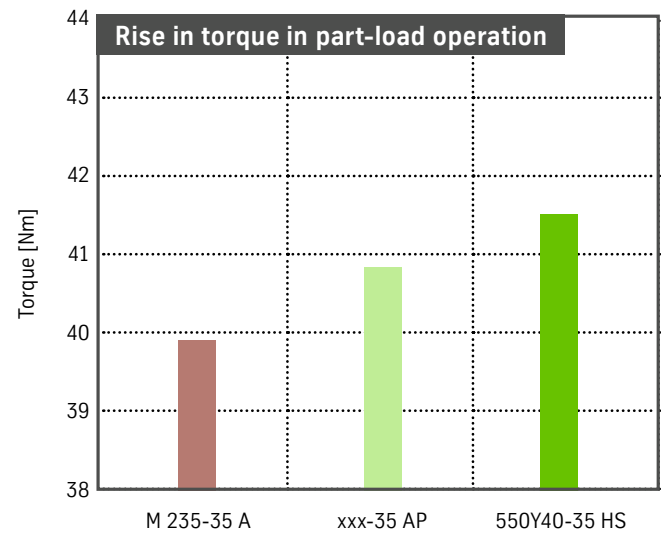
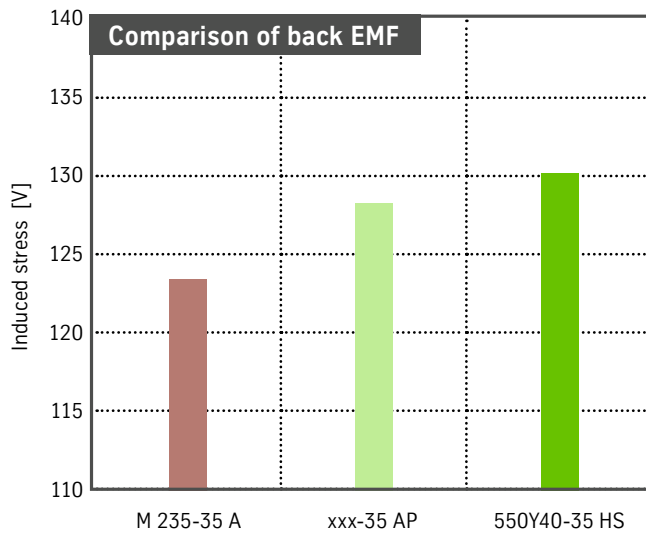
The Powercore Explorer is available as an expert tool for selecting the most suitable, non-grain-oriented electrical steel grade and for supporting the FEM simulations, 7. It encompasses the soft magnetic characteristics and data of various electrical steel grades of samples measured in the Epstein frame, also for high frequencies of over 400 Hz, for example. The tool also offers the option of exporting the material data directly into conventional FEM simulation programs. This enabled the material magnetization and loss data measured in InCar plus to be quickly integrated into the simulation.

To validate the simulations, three prototypes were built and measured on the motor test rig at the E-Mobility Center Drives in Bochum, 8.

The values measured for the three motors on the test rig underpin the simulation results. Increases in the back EMF and the torque clearly indicate the advantages of the high-strength electrical steel, 9. In the next step, the machines' measurement results are used to refine the simulation models.



8 Cores including stator winding (left) and a prototype of a machine (right)



⑨ Parameters measured at the nominal speed of 4000 rpm

In addition to the mechanical simulation at 14,400 rpm, all three rotors were run at different speeds until they ruptured and the rotor expansions were also measured. The investigation took place both at room temperature and at 150 °C, as the mechanical characteristics such as yield strength or tensile strength deteriorate at increasing temperatures. The overspeed results correlate to the mechanical simulation results. With these overspeed and simulation data, ThyssenKrupp is simultaneously increasing its know-how regarding the relationships between material tests and component tests.

BONDAL E IMPROVES THE ACOUSTICS OF ELECTRIC MOTORS

The three-layered composite material Bondal E in the stator of an electric motor reduces sound emissions by up to 10 dB(A). Bondal E's high structure-borne sound damping is the reason for this and is achieved thanks to a very thin intermediate layer of polymer material. The stacking factor therefore remains virtually unchanged and the electric motor's power-to-weight ratio is retained. Due to the electric motor's reduced sound emissions, secondary soundproofing measures can be dispensed. Therefore, package-, weight- and cost reductions must be anticipated in the overall system.

Bondal E is currently being developed specifically for use in electric motors and can significantly improve acoustics thanks to its very good damping characteristics. The composite material has a three-layer structure consisting of two cover sheets with a viscoelastic intermediate layer. Bondal E can be stamped using conventional stamping tools and then assembled.

For use in the stator of an induction motor, the Bondal E cover sheets are manufactured from non-grain-oriented electrical steel of grade M 235-35 A with a C5 coating (Stabolit 20) and a sheet thickness of 0.35 mm, ❶. The viscoelastic intermediate layer is very thin as well

as oil- and temperature-resistant. The stacking factor, which is very important to an electric motor's efficiency, is only reduced by around 0.7 % due to the selected combination.

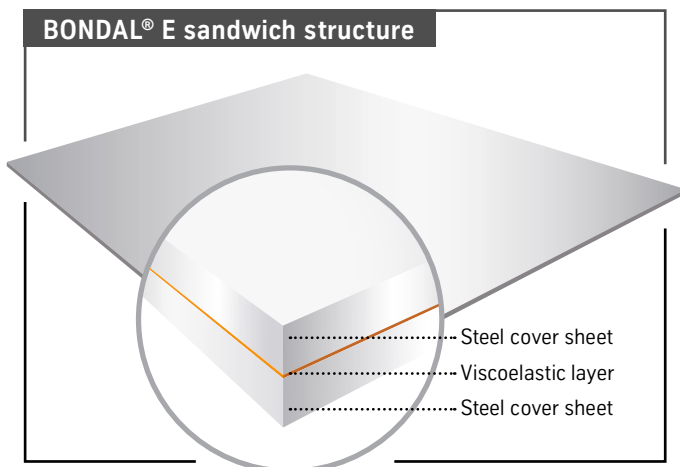
Bondal E's structure-borne sound damping is responsible for the induction motor's reduced sound emission. A loss factor of $\eta = 0.05\text{--}0.11$ in the typical acoustic frequency and temperature range is measured for the composite material according to the EN ISO 6721 standard. Non-grain-oriented electrical steel without this layer only reveals a loss factor of $\eta < 0.001$.

For a precise comparison, an electric motor is constructed with a Bondal E

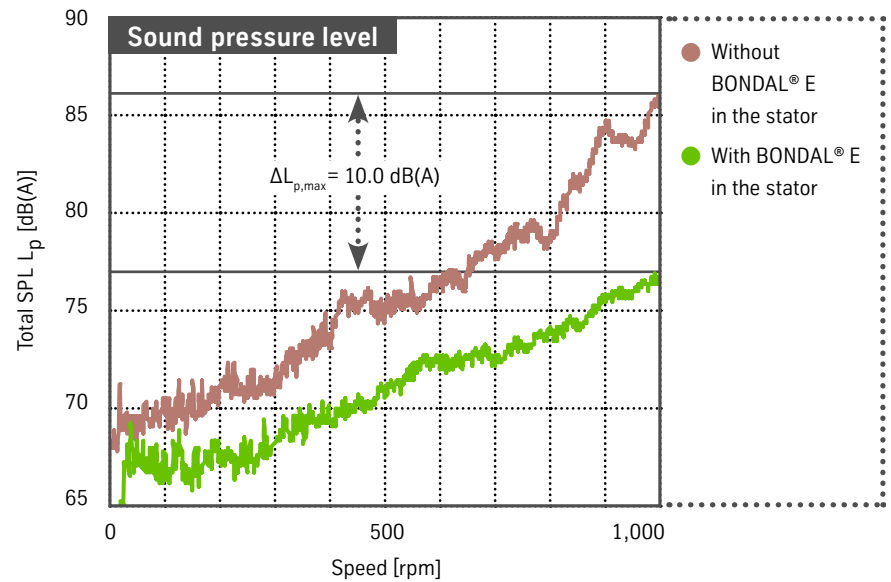
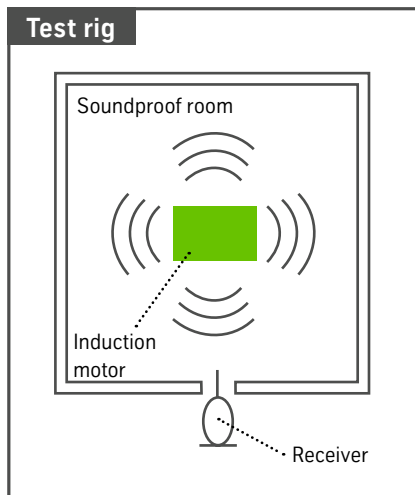
stator. As a reference, an identically designed electric motor has the same electrical steel grade M 235-35 A without viscoelastic intermediate layers. The two induction motors are installed in an acoustically defined environment and the sound pressure level is measured during machine rev-up, ❷. To do this, the rotational speed of both machines is increased from 0 to 1000 rpm within 45 s. The absolute sound pressure level measured in this process is reduced by up to 10 dB(A) due to the use of Bondal E.

However, noises cannot be described solely using the purely physical measurement variable of sound pressure. The tonality also determines whether noises sound more or less pleasant. This psychological perception is reflected in the Campbell diagram, ❸. Close and dominant frequency bands lead to a strong and unpleasant tonality. In the conventionally designed reference induction motor, two dominant frequency bands occur at around 500 and 950 Hz. When Bondal E is used in the stator, no dominant frequency bands can be measured; the noise has broader bands and is therefore perceived as more pleasant.

The good effectiveness of the new material is also proved by the representation of the vibration forms in the transfer path analyses. The amplitudes of the vibration forms in the dominant



❶ Structure of Bondal E: electrical steel as cover sheets with viscoelastic intermediate layer



② Schematic structure of the test rig and comparison of the total sound pressure level of the rev-up measurement

frequency bands are significantly reduced through the use of Bondal E.

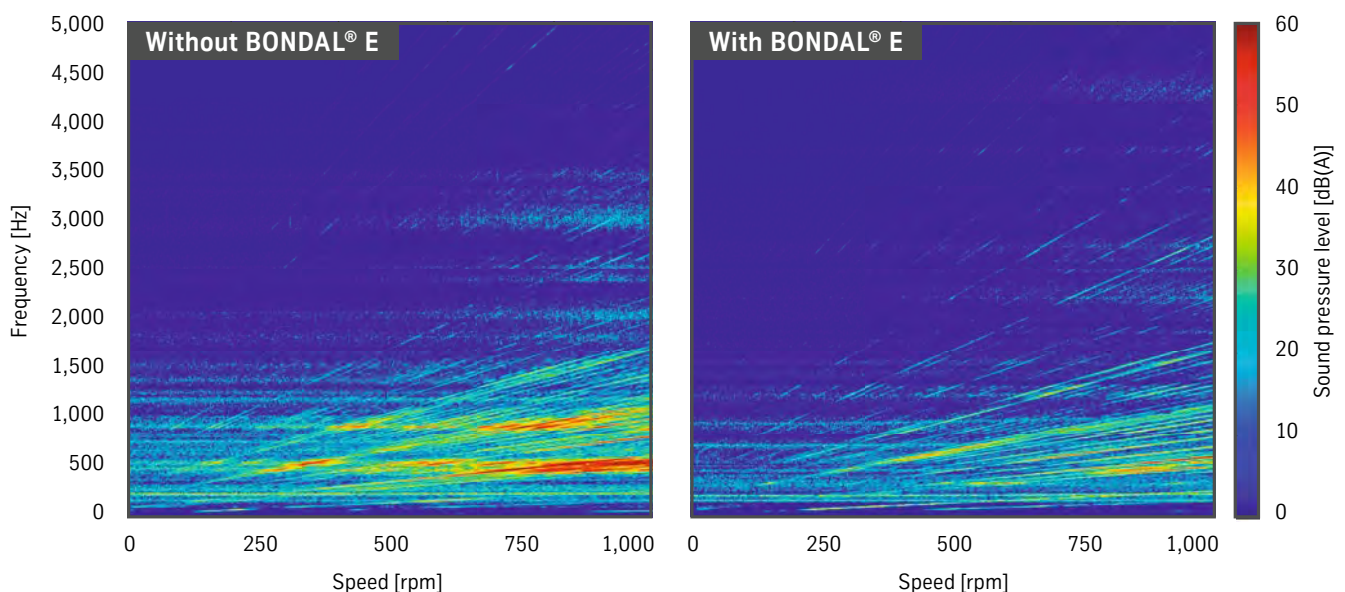
The soft magnetic properties are characterized on the basis of a toroidal core sample. The specific magnetization energy and the permeability are determined. Comparison of these key values reveals no significant deterioration between the new Bondal E and the conventional, non-grain-oriented electrical steel.

OUTLOOK

Due to these very interesting results, further Bondal E studies are planned. Above all, work is focused on developing a large-scale production process and the technical boundaries for the sheet and intermediate layer thicknesses which can be processed.

The sheet thicknesses of the non-grain-oriented starting material for sta-

tors are currently being further reduced in order to increase the efficiency of electric motors, especially high-performance motors for passenger cars. However, thinner sheets mean increased processing effort in stator manufacturing. Bonding two thin sheets increases stiffness and facilitates processing. New insulating lacquer and intermediate layer combinations are being developed to further increase the stacking factor.



③ Campbell diagram of the rev-up measurement; conventional induction motor with dominant frequency bands at 500 and 950 Hz (left), with new Bondal E in the stator (right)

LIGHTWEIGHT ROTOR WITH INTEGRATED COOLING SYSTEM

As main energy converters in electrified vehicles, electric machines play a key role in tapping efficiency potentials. As part of InCar plus, ThyssenKrupp is pursuing the holistic approach of a hollow cylindrical lightweight rotor architecture: the multi-part, modular structure of the rotor saves up to 16 % weight and generates a freely usable package of more than 800 cm³ within the rotor in comparison with the reference machine. Active rotor cooling can be integrated into this to further improve efficiency.

Electric motors for stationary applications are not usually designed with weight reduction in mind, as this is typically not a key requirement. By contrast, in vehicle drives the rotational and translatory masses of the electric motors significantly influence energy consumption and thus the size of the battery. Moreover, weight should be as low as possible in this case.

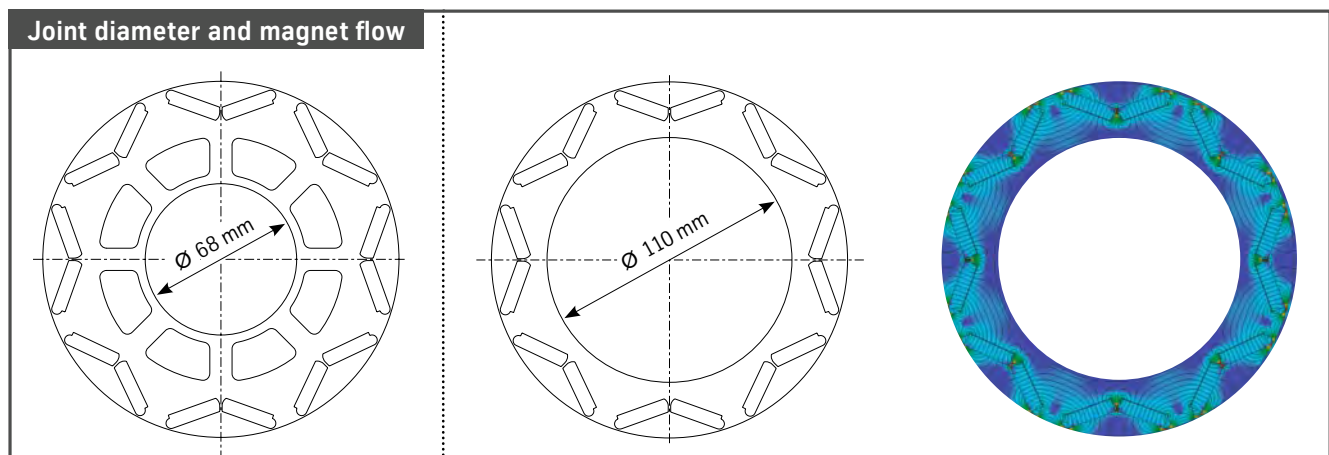
However, the majority of electric drives available on the market are fitted with single-piece, often solid shafts with small diameters. While shafts designed in this manner are not heavy, the overall rotors with the assembled laminated cores are due to their design. A familiar approach for reducing weight is to punch

out partial areas of the inactive sheet metal zones. A spoke design is commonly used for this, ❶ (left). In all, these rotors are only slightly lighter than rotors for stationary applications, e.g. for machine tools.

Conversely, an architecture restricted to the laminated core cross-section through which the magnetic flow is extending can significantly reduce the weight. A maximum laminated core hole diameter and shaft outside diameter are selected to achieve this, ❶ (center). Inactive filler material between the rotor shaft and active electric sheet material, however, is consistently omitted, ❶ (right). A laminated core designed in this

manner is 1.9 kg lighter than that of an otherwise comparable rotor. This lower weight is of particular importance to drive efficiency since a rotating component is involved. The rotational mass moment of inertia of the laminated core bearing the magnet is over 6 % lower in this design. This factor offers efficiency advantages in the acceleration process.

For over a year now, ThyssenKrupp has been manufacturing and supplying such assembled rotor shafts on specific assembly and grinding equipment for a production vehicle, ❷. The rotor shaft designed for a small, battery-powered electric vehicle has hardened shaft journals with outer knurls for a press- and



❶ Metal rotor sheet sections and magnet flow curve at the 4000 rpm operating point, 150 Nm

Assembled rotor shaft

② Production solution for a multi-part, assembled rotor shaft

form-fit joint with the center tube section. Even with pressing lengths of less than 15 mm, this design enables the transmission of very high torques from the rotor cores to the transmission connection by means of inner splines.

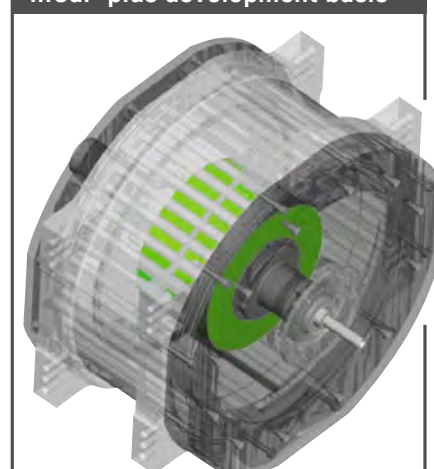
ELECTRIC MACHINE EXPERTISE

Based on the standard rotor shaft, ThyssenKrupp is continuing to develop the structure of the overall rotor with laminated cores and is exploiting the

design-based advantages to integrate selected functions. Due to its power output density and efficiency advantages as well as its current market penetration, the drive used for this project is a permanent magnet synchronous motor (PMSM) with an operating voltage of 600 V. In addition to lightweight design and function integration, the objective of the project is also to use material expertise within the company. The non-grain-oriented electric steel sheets used for the laminated stator and rotor cores as well as the NdFeB (neodymium-iron-boron) permanent magnets are in-house products.

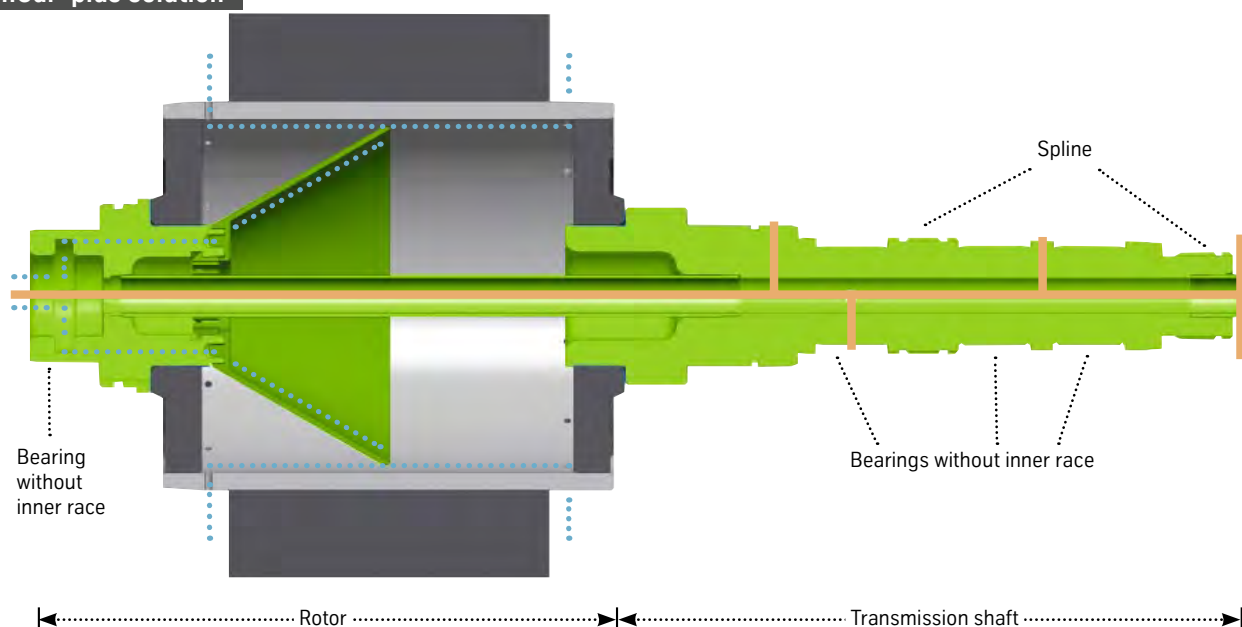
This interdisciplinary technology expertise is generating further valuable information for the development work. Using electromagnetic simulation, the eight-pole electric machine was designed with a NdFeB magnet mass of 1.45 kg and a laminated core with an optimized weight of 5.8 kg, ③. ThyssenKrupp was supported in this by the Institute of Electrical Machines (IEM) at RWTH Aachen.

The drive is designed as a “standalone” machine for testing and inverter parameterization, and is used in the eTDC transmission, another InCar plus development

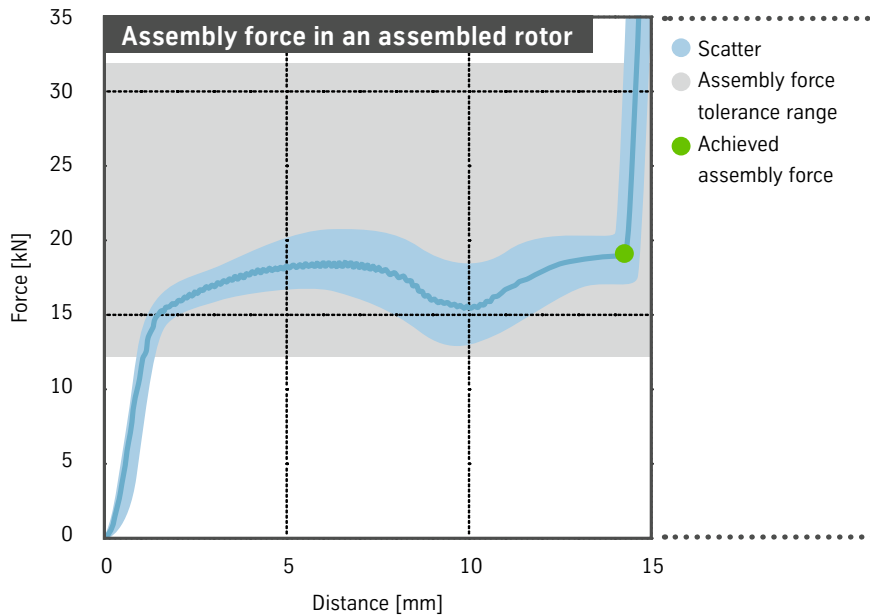
InCar®plus development basis

③ Structure of the electric PMSM machine

project (see article “Shafts with Optimized Packaging and Costs for Electric Drives” from page 38). The design parameters for the electric machine and the specific rotor shaft design are also derived from the eTDC transmission. The nominal power output is therefore 50 kW, and the peak power output 80 kW. The torque is defined as 220 Nm (nominal value) and

InCar®plus solution

④ Function areas of the assembled, integrated rotor and gear shaft



5 Example of process control through force/distance monitoring

300 Nm (peak value). The maximum motor speed is 8000 rpm.

MODULAR ROTOR CONCEPT

ThyssenKrupp has formulated the following development objectives for the lightweight rotor:

- : integrated function of a gear shaft with two splines and seats for idler gears
- : bearing without inner ring (roller contact directly on ground shaft surface)

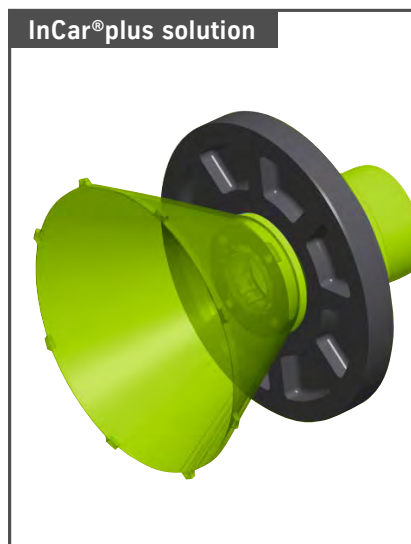
: intake, channeling and output of lubricating oil and cooling of the inner rotor surface in a separate, switchable circuit. One significant manufacturing advantage of this innovative rotor architecture is its multi-part design. As the bearing points and other functions at both ends of the rotor reveal vastly smaller diameters than the lamination core hole diameter, a basic five-part structure of the shaft is sensible, 4.

The center section is a tube consisting of inexpensive structural steel bright

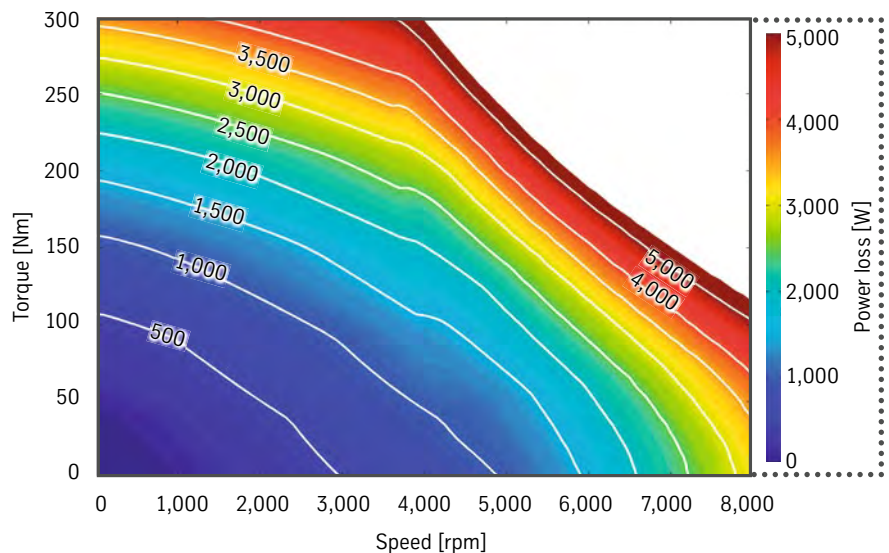
drawn to near the final dimensions. What is more, varying the tube length also enables the machine length to be varied. The tube wall thickness and interference fit assemblies are calculated based on the hole diameter of 110 mm with an air gap diameter of 160 mm determined for the laminated core in the simulation.

A common parts concept exists for the bilateral flange plates. In production they can be manufactured cost-efficiently and almost to the final geometry as hot stampings. Machinable tolerances are sufficient with regard to the flange plates for the inner and outer joint diameter press fits. The special features on the plates are the spokes for optimizing weight and stiffness plus an axial protrusion for balancing the overall rotors in two planes. The rotor shaft journals consist of high-quality, alloyed CrNiMo steel which enables bearings without inner rings and hardened spline profiles. Influences reducing the joining pressure such as the temperature gradient between the laminated core at operating temperature and cold shaft, surface roughness smoothing and the rotational speed-dependent centrifugal force have already been taken into consideration for the press fit.

The rotor shaft joints are produced in force fit at room temperature and are recorded for each component by means of force/distance monitoring. The pressure force at the end of the joining



6 Mounted oil guide cone



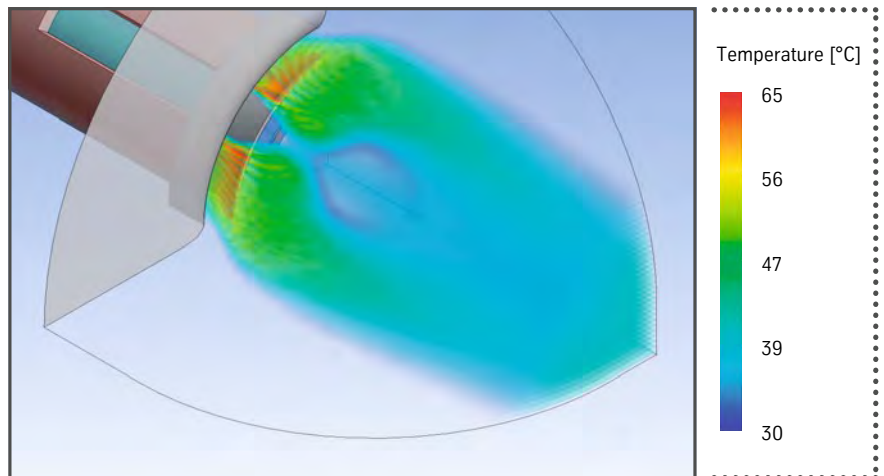
7 Electric machine loss map

travel is a central process characteristic which can be used to reliably determine component manufacturing according to the specifications, ⑤. Complex measurement of the component characteristics are therefore not necessary. The press-fit force for each joint also validates the torque to be transmitted.

INTEGRATED COOLING

There are only few examples of internal cooling implemented in a rotor. They are usually based on single-part, thin shafts. As a result of this, however, the design of the shafts limits heat dissipation. Such concepts are often restricted to flow through a deep-drilled hole, necessitating a high cooling medium volumetric flow in addition to the costly machining.

Cooling also reveals a further advantage of the multi-part shaft. For example, specific parts such as an oil guide cone can be installed in the interior of the rotor during assembly, ⑥. This funnel-shaped component is intended to guarantee that the entire inner rotor surface is wetted with cooling medium, in this case transmission oil, with low volumetric flows. A large interaction surface and a high-performance medium such as transmission oil are therefore available for cooling the interior of the electric machine. The rotational speed-dependent cooling flow is



⑥ Outflow side of the gas-cooled rotor

around 500 ml/min and is determined according to the operating points in the electric machine's operating map, ⑦.

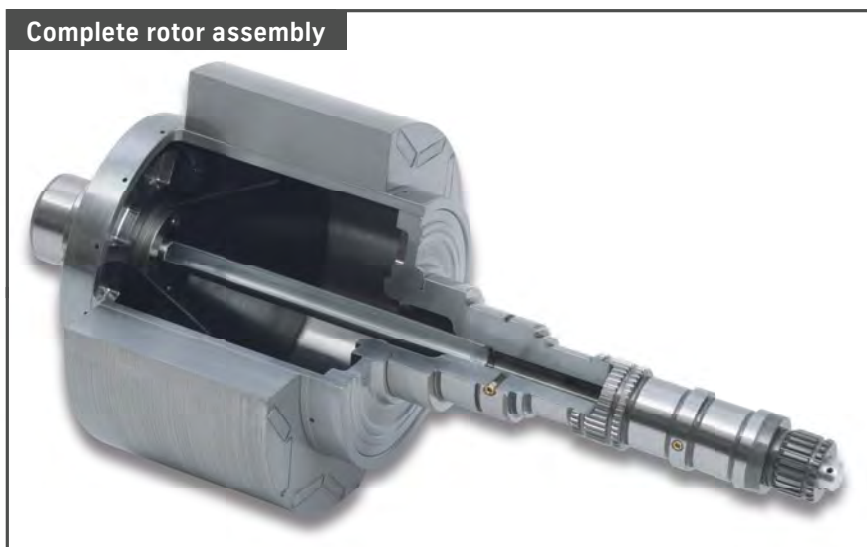
The development team also investigated gas cooling using ambient air. At approximately 3.5 l/s, the required volumetric flow is significantly higher. Inside the rotor, a heat sink consisting of an extruded aluminum profile enlarges the surface. Rig tests verify that fast and turbulent gas through-flow offers sufficient cooling, ⑧. A diagonal armature rotating passively at the end of the rotor shaft generates the flow with a required power of less than 2 W. The air should be cleaned in an intake filter with 60 ppi to reliably prevent dust particle entrainment.

Outflowing air temperature measurements reveal heating rates of more than 30 °C in comparison with the ambient air at intake.

OUTLOOK

In addition to cooling, further functions can also be integrated into the interior of the rotor. Systems integrated should not result in any additional thermal losses inside of the electric machine, which is in any case thermally limited. These may include motor sensors for angular position and rotational speed or a mechanical parking brake, which is also specified for electrically operated vehicles by legislation.

Joining the laminated cores requires particular attention in the future, especially in view of the high-speed concepts. As an inexpensive alternative to the thermal shrink-fit seat, the baked lacquer cores for the InCar plus rotors are joined in the longitudinal press-fit process with force monitoring. A newly developed concept is also being studied: joining punched cores by axial clamping. This innovation enables the transmission of high torques without any radial contact between the shaft and sheet metal plates by guiding the flow of force via the pressure plates at the ends. Such prototypes are currently undergoing static and dynamic testing. With this development, ThyssenKrupp has acquired extensive expertise which forms the basis for future production supply of the overall rotor assembly, ⑨.



⑨ Rotor with integrated gear shaft assembly

SHAFTS WITH OPTIMIZED PACKAGING AND COSTS FOR ELECTRIC DRIVES

The core requirements on all electric drives are maximum efficiency and optimal power output with minimal costs and small dimensions. In the eTDC project (electromobile ThyssenKrupp Drivetrain Components), ThyssenKrupp is showing how an intelligent drive structure with innovative lightweight design components can resolve these conflicting aims. The assembled, integrated rotor/gear shaft enables tailored material selection with high economy at the same time. Thanks to the use of an optimized joining method, the omission of the transmission interface and the integration of functions, this concept offers essential advantages as regards the overall package, weight and efficiency.

At present, passenger cars driven by electric batteries are primarily fitted with one-speed transmissions with fixed, two-stage reduction and a high-speed electric motor. This configuration is usually chosen due to cost and weight rea-

sons. However, it is subject to compromises in terms of efficiency, acceleration and the achievable vehicle speed. Two-speed transmissions can offer better efficiency and acceleration as well as a higher top speed, but previous concepts

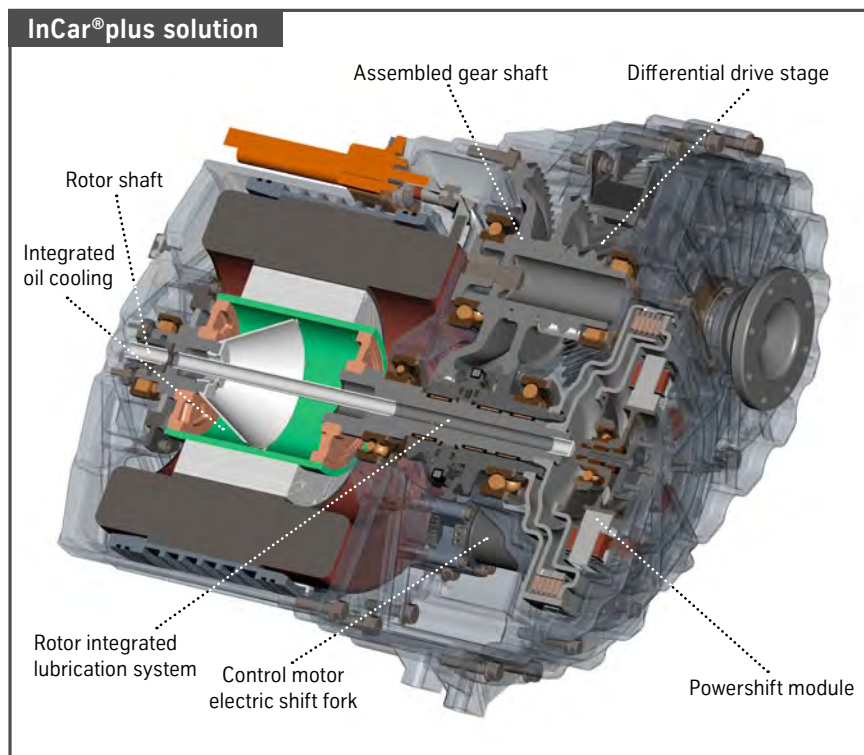
have not been accepted by the market due to cost and weight.

As part of InCar plus, ThyssenKrupp has optimized rotor and gear shafts for innovative, electrified vehicle drives, ①.

An independent drive structure was established to extensively evaluate the requirements and quantify the potentials, ②. The essential boundary conditions and requirements on the drive are:

- : small cars (B segment)
- : curb weight including battery 1450 kg
- : maximum vehicle speed 140 km/h
- : acceleration from 0 to 100 km/h in less than 10 s
- : gear changes without tractive power interruption
- : conceptual flexibility and modularity
- : minimum weight and package.

The eTDC drive structure is based on a spur gear architecture, which offers maximum gear ratio flexibility with a simple system design at the same time. The idler gears for first and second gear are mounted on the assembled, integrated rotor/gear shaft. The positively shifting double tooth coupling for both gears is located between the two idler gears. Their integration combined with the omission of synchronizer rings is possible due to the electric traction machine's precise speed regulation. This design offers significant advantages in terms of efficiency, system complexity and costs. A multi-plate clutch mounted



① Cross-section of the eTDC drive

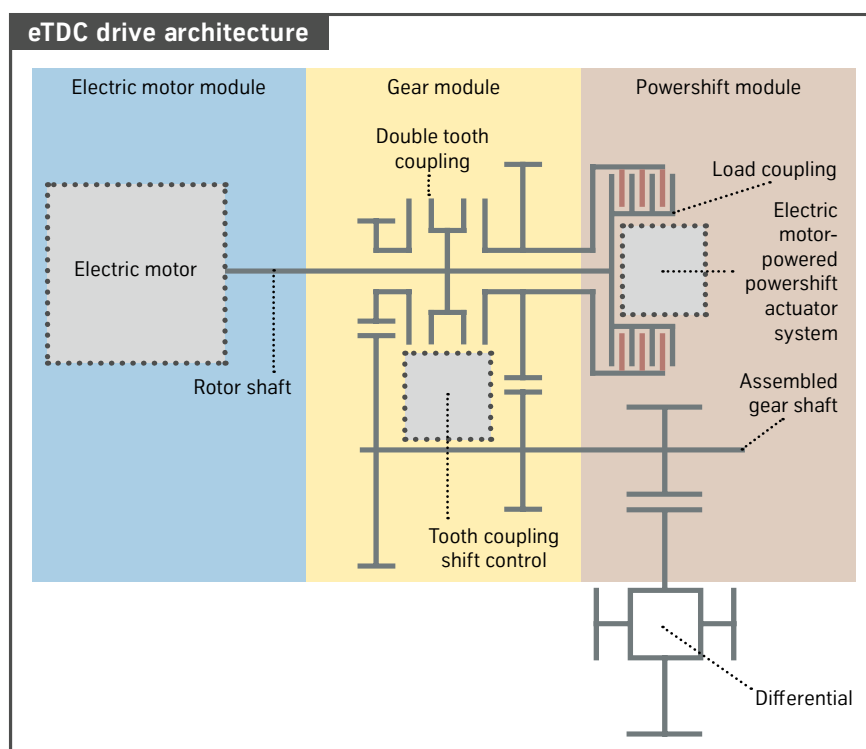
on the face end of the rotor shaft ensures shifting without torque interruption. Simultaneous actuation of both shift elements enables a cost-efficient parking lock without package impact. Additional components can be foregone for this. Both shift elements are actuated electrically and therefore significantly reduce ancillary assembly losses. The intermediate shaft with the fixed gears is designed using an assembled lightweight structure, ③. The resulting conceptual modularity and flexibility enable the highly efficient drive to be used in various vehicle applications.

DRIVE CHARACTERISTICS AND DESIGN

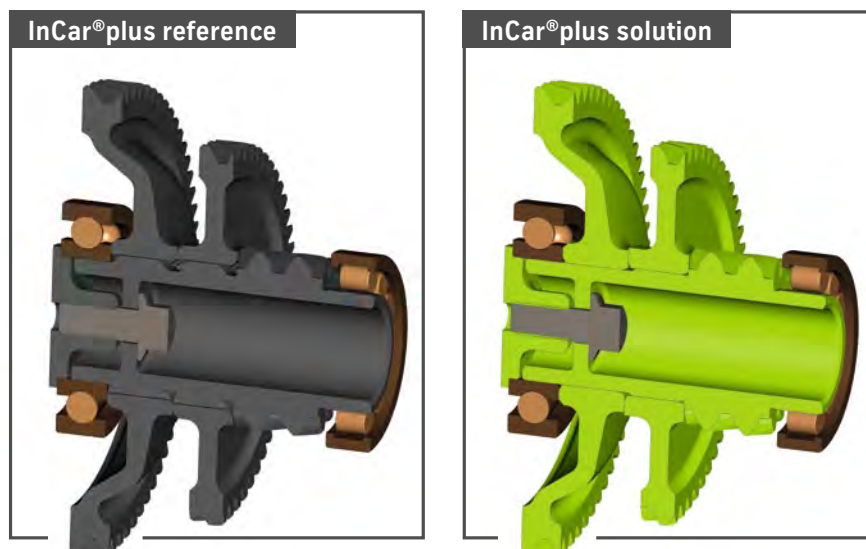
The efficient, permanently excited synchronous machine with a rated voltage of 600 V and a current maximum speed of 8000 rpm results in a high power density. It develops a permanent power output of 50 kW and 220 Nm of torque. Temporary peak values of 80 kW and 300 Nm are possible. The five-piece, assembled rotor shaft (also see article “Lightweight Rotor with Integrated Cooling System” from page 34) is the drive’s central component. It comprises three different materials and is the integral link between the electric motor and the gear module.

The lubricating system can be integrated into the rotor shaft by extending the functions on the transmission side and thanks to the omission of a transmission interface which is tolerance-sensitive and thus technically complex to manufacture. The newly developed oil cooling system is also integrated into the rotor shaft. It uses the rotor’s kinetic energy and very effectively dissipates the heat from the rotor’s laminated core, and the thermally stressed winding heads. The oil cooling system can be engaged depending on the operating point and also enables the transmission oil to reach its operating temperature faster during the warm-up phase. This dual function integration improves the drive’s electric and mechanical efficiency and minimizes the package and weight. Including the laminated core, the rotor shaft weighs just 11.4 kg.

③ shows a cross-section of the assembled gear shaft. The fixed wheels are connected by means of a press and form-fit joining process used in the mass pro-



② Functional breakdown of the eTDC development basis



③ InCar plus reference gear shaft (left) and InCar plus assembled gear shaft (right)

duction of engine components and has been optimized to meet the specific requirements of a transmission application. The maximum torque of 900 Nm is transmitted with a dynamic safety factor of 2 over a short joint length. This ensures a short axial length of the overall component as well as high durability at the same time. Optimized shaft wall thicknesses also effectively reduce the

weight of the basic shaft. Recording the assembly force for each component guarantees complete quality monitoring during manufacturing.

One further element of the drive’s efficiency is the passive oil system. In combination with the differential’s pumping effect, the gravitational pressure and the suction effect of the rotor shaft, it supplies the lubrication system and the cool-

eTDC drive



④ eTDC has a two-speed transmission as its development basis

ing system with sufficient oil in virtually all operating states without an active pressure generator. Depending on the vehicle layout, driving situations involving high lateral acceleration may necessitate an electric auxiliary pump. This can be integrated into the design of the transmission structure. All in all, this results in a compact, modular drive layout with a very low number of components and a total weight of less than 100 kg, ④.

VIRTUAL VALIDATION AND TESTING

The overall system is subjected to extensive analytical and numerical validation in several development stages. To do this, comprehensive static component layouts, FEM evaluations, modal analyses and multi-body simulations were performed. The focus was placed mainly on detecting areas of resonance throughout the entire speed range and on determining the resulting dynamic stresses.

Consideration was given to the bearing, housing and the changing tooth stiffness in the latter.

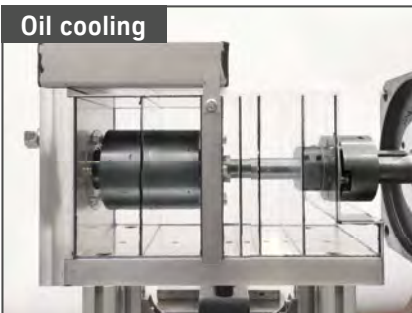
The overall system achieves the highest cyclical operating rates in the area of the rotor shaft in first gear. Amongst other factors, this results from the second gear's coupled assemblies at a speed of 3800 rpm. A safety factor of greater than 2 is achieved for this load case.

To determine the required mechanical, electric and thermal parameters, the electric actuators and the oil system were tested on sub-system test rigs, ⑤. In combination with validated simulation models, these tests enabled the corresponding validation of functionality and implementation in the overall prototype.

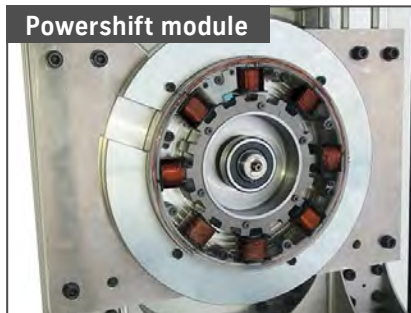
To initially quantify the overall system efficiency, the engineers performed a holistic powertrain simulation based on the power loss models of all components and systems in the energy and power flow. Based on the previously defined vehicle weight of 1450 kg, energy consumption of 11.3 kWh/100 km is determined in the NEDC. eTDC therefore offers substantial efficiency potential with both a small package and low weight.

In the fall of 2014, the drive system will undergo extensive system testing on test rigs. The results obtained from simulation and component tests will be further validated there in intensive tests. The focus will be placed on the durability and operating behavior of the overall system.

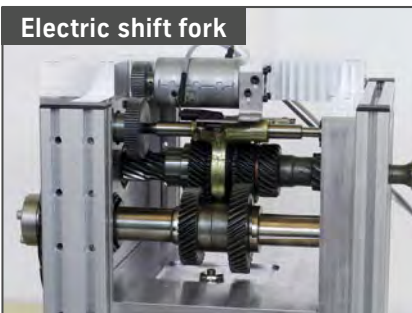
Oil cooling



Powershift module



Electric shift fork



⑤ Development test rigs for the sub-systems

LIGHTWEIGHT, ELECTRIFIED STEEL REAR AXLE

Due to its many positive properties, steel is also indispensable for the development of electrified vehicles. A concept study that uses the example of an electrified rear axle as part of a hybrid drive system reveals some of the specific potentials of steel lightweight design. The electric drive unit is integrated into a rear axle sub-frame that has been optimized with regard to its package and weight.

In the concept study, the electrified rear axle forms part of a hybrid drive system. The primary objective is to integrate the axle into an existing vehicle concept without significantly modifying the overall structure of the vehicle. Accommodation of other major components such as battery and power electronics is also taken into consideration.

ThyssenKrupp uses a six-cylinder internal combustion engine with four-wheel drive as a reference for its concept study. This reference powertrain is replaced by a four-cylinder engine with front-wheel drive and an electric motor integrated into the sub-frame of the multi-link rear axle, which drives the rear axle when required. This combination offers comparable performance and similar accel-

eration. What is more, the vehicle is designed to have a pure electric driving range of at least 50 km in normal traffic.

The modified subframe is designed and calculated so that it can be inserted into the reference powertrain's package and meets the same requirements. As the vehicle has front-wheel drive, there is no need for a drive shaft to the rear wheels, which means that the battery can be installed in the center tunnel. Considering the energy density currently possible, a battery with a capacity of approximately 10 kWh can be accommodated in this package. Smaller components such as the power electronics are installed either in the floor of the luggage compartment or in the front of the vehicle alongside the downsized internal

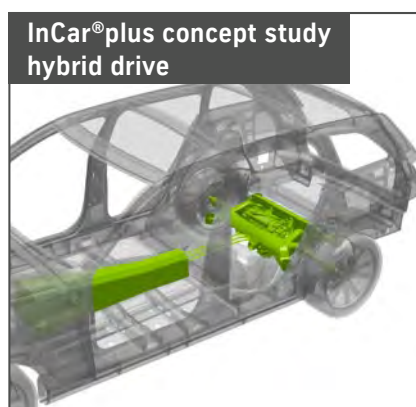
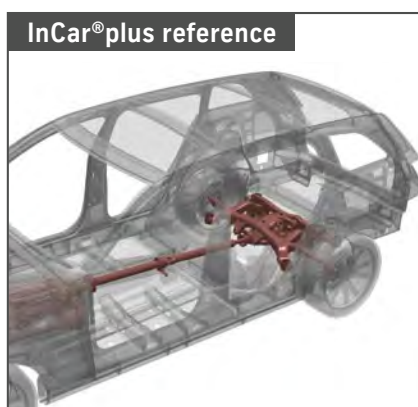
combustion engine. The electric motor is water-cooled and can be connected to the combustion engine's cooling circuit, as this has been designed for the original, significantly larger six-cylinder engine. All additional components required for the hybrid drive are therefore housed in the existing vehicle structure's package, ❶.

DESIGN OF THE ELECTRIC MOTOR

The electric motor with transmission is integrated into the rear axle subframe. A peak power output of around 90 kW is required to achieve the specified acceleration values, ❷. As the electric motor is not decoupled and continues running up to the top speed of 200 km/h, an induction motor has been selected due to its very low drag losses.

The maximum possible outside diameter of the stator due to the package is 210 mm. To attain the required peak power output of 90 kW, a package length of 210 mm is also necessary; a maximum rotational speed of 15,000 rpm has been taken as the basis. Grade 440-35 AP non-grain-oriented electrical steel with high polarization and good magnetization capability has been used as the material for the stator and rotor. The rotor has a die-cast aluminum cage. To improve efficiency, the implementation of a copper rotor is also planned.

After a power loss map has been calculated, a longitudinal dynamics simulation is carried out to determine the performance and energy requirements.



❶ Comparison of reference structure with conventional powertrain (left) and hybridized InCar plus solution (right)

	InCar®plus reference	InCar®plus concept study hybrid drive
Combustion engine		
Power output	225 kW	135 kW
Torque	400 Nm	270 Nm
Cylinder	6	4
Displacement	3.0 l	2.0 l
Electric motor		
Power output (duration/peak)	Combustion engine only	40/90 kW
Torque (duration/peak)		100.6/226.3 Nm
Maximum speed (rpm)		15,000 rpm
Performance and energy consumption		
Acceleration 0-100 km/h (combustion engine or hybrid/pure electric)*	5.6 s	5.9 s/13.1 s
NEDC consumption (pure electric)	Combustion engine only	15.1 kWh/100 km
Battery capacity		10 kWh
Electrical range (use of 80 % of battery capacity)		53 km
*Target values: Hybrid: < 6.0 s/pure electric < 16.0 s		

② Technical data and performance of the reference and concept study

Due to the limited package and costs, the transmission is of a two-stage design with fixed reduction. The total reduction is 8.811 (1st stage: 2.033; 2nd stage: 4.333). The transmission is completely validated by simulation using the parameters determined from the longitudinal dynamics simulation. Its bearings and gears are designed to withstand the

stresses of hybrid use. Component lubrication is ensured by a passive lubricating oil supply. If necessary, a switchable oil pump can actively cool the rotor from the inside. The induction motor is water-cooled using cooling lines cast into the housing, ③. To optimize the packaging, the output shaft is coaxial, for which reason the rotor shaft has to be hollow.

The most efficient solution for this is a hollow shaft assembled using a tube and further components.

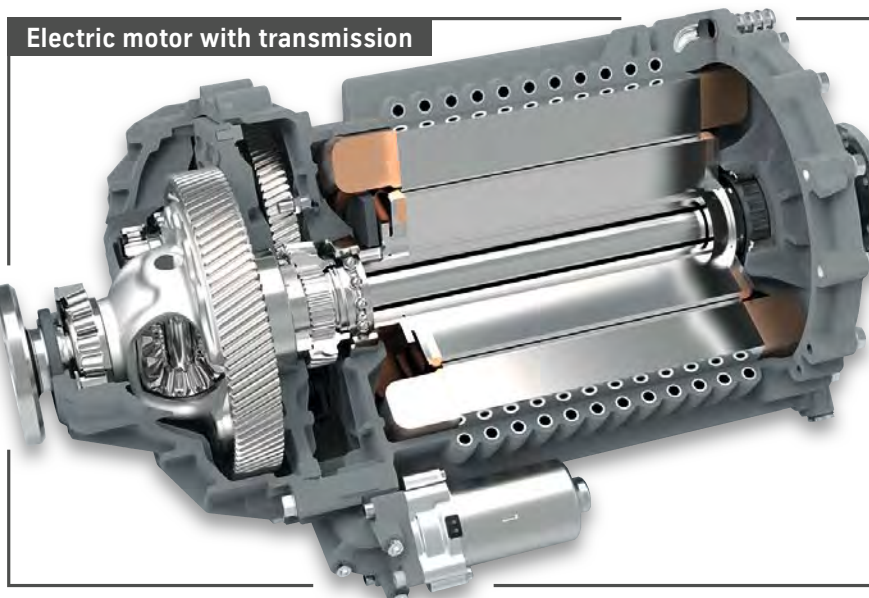
DESIGN OF THE REAR AXLE SUBFRAME

The geometry of the rear axle subframe is adapted to the electric drive. The cross-members feature significantly reduced dimensions to ensure that the lines and connections for the control and power electronics as well as cooling water remain accessible even in the extensively limited package. High-strength steel grades such as complex phase and Scalur steels are ideal materials for the rear axle subframe, as they are able to withstand the high loads and stresses thanks to their high strength with slim cross-sections and low sheet metal thicknesses. At the start and end points, the weld seams are designed to minimize notch effects. Laser hybrid welding offers further potential for improving the welded joints. The use of profiles joined without flanges also leads to the minimization of welding seam stresses. In comparison with the reference, in which conventional steel grades are used, the combination of high-strength steel grades and modern manufacturing and joining techniques results in a weight reduction. This compensates the price of the new steel grades, leading to expectations of cost neutrality.

As the body connecting points and the kinematics are also identical to the reference, the electric drive, together with the rear axle subframe, can be integrated into the existing vehicle with just minor adaptations. This offers the advantage that the modular hybrid drive can be fitted into a conventional vehicle with a combustion engine and therefore no specially developed vehicle structure is necessary.

OUTLOOK

Thanks to its future-capable material properties, steel is also the first choice for the electrified vehicles of the future. Modern joining and manufacturing processes enable new concepts and designs for further lightweight design potential. Progress in surface technology will additionally lead to improved corrosion properties and therefore enable sheet metal thicknesses to be reduced even further.



③ Sectional view of the electric motor with water cooling and transmission

PLASMA-MODIFIED BIPOLAR PLATES FOR FUEL CELLS

Fuel cell stacks with bipolar plates consisting of surface-modified stainless steel stand out for their space- and weight-saving design. This means that, in theory, an electric zero emission drive with ranges of more than 500 km is possible. This preliminary study shows development approaches for bipolar stainless steel plates which reveal high corrosion resistance and electrical conductivity thanks to plasma modification. They are approximately 60 % cheaper than gold-coated stainless steel bipolar plates. In comparison with bipolar plates consisting of graphite composite, the bipolar stainless steel plates are around 5 % lighter and roughly 25 % smaller.

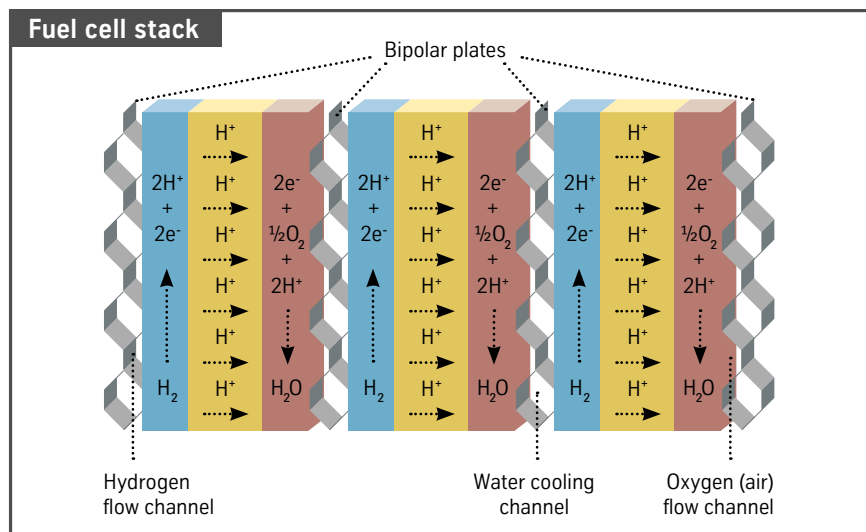
Bipolar plates connect several hundred individual fuel cells to form a high-performance stack, ❶. They not only ensure that the cells are electrically connected to each other but also conduct the hydrogen and air to the cells and remove water and heat which have occurred there. The requirements on bipolar plates arise from these tasks: they must be highly corrosion-resistant and electrically conductive in acidic electrolytes. At the same time, they should enable a very compact design to minimize spatial requirements and weight. Technically, there are two solutions at present: bipolar plates consisting of graphite composites or gold-coated stainless steel. The former are comparatively heavy and require a lot of installation space; the latter are very expensive even when mass-produced. Cost-efficient modification of the steel surface with very good electrical conductivity is therefore desired. However, it must not affect the stainless steel's corrosion resistance in acidic electrolytes, an aspect which is vital for use in fuel cells. Fundamental development and assessment of the entire manufacturing process, including plasma-supported coating of the steel, are required for possible volume production.

This preliminary study reveals alternative development approaches for a

surface-modified stainless steel bipolar plate in comparison with the above mentioned reference solutions. Their essential characteristic is treatment of the steel surface with carbon and nitrogen. Important characteristics in comparison with the two reference solutions are summarized in ❷.

Development focus in the preliminary study is on corrosion resistance and electrical conductivity. The US Department

of Energy (DOE) development objectives are the benchmark for these characteristics. Two different manufacturing processes are studied to achieve economic production. Firstly, plasma modification of formed bipolar plate halves and subsequent joining to form the finished bipolar plate. Secondly, plasma modification of the flat steel product with subsequent forming and joining of the bipolar plate. The second manufacturing process



❶ Schematic view of part of a fuel cell stack including bipolar plates and their functions

Feature	InCar [®] plus solution	InCar [®] plus references	
	Plasma-modified stainless steel	Gold-coated stainless steel	Graphite composite
Corrosion resistance	● ● ○	● ● ○	● ● ●
Electrical contact resistance	● ● ○	● ● ○	● ● ●
Package space reduction	● ● ●	● ● ●	● ○ ○
Weight reduction	● ● ○	● ● ○	● ○ ○
Cost reduction	● ● ○	● ○ ○	● ● ○

② Comparison of the characteristics of various bipolar plates

● ● ● Very good ● ● ○ Good ● ○ ○ Neutral

is based on a continuous strip process with high productivity and economy potential.

DEVELOPMENT IN COOPERATION

③ shows two finished bipolar plates as advanced prototype components produced according to the second manufac-

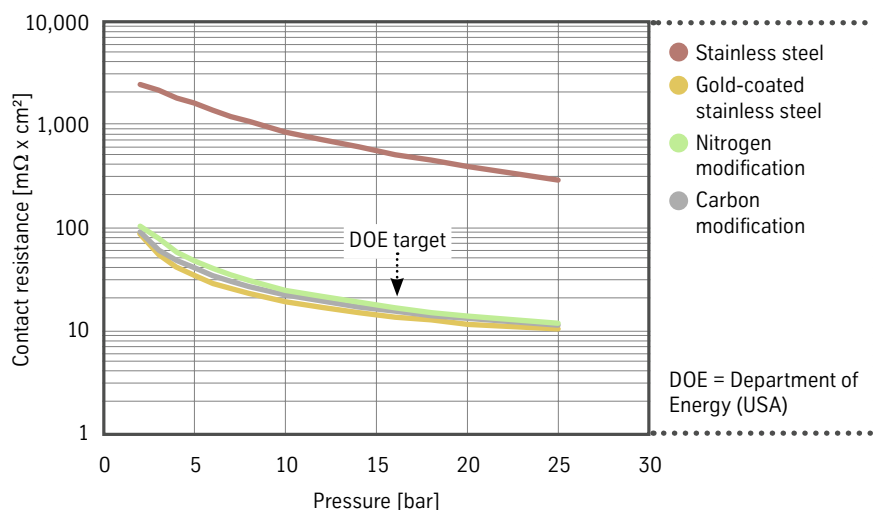
turing process. Their surfaces reveal excellent electrical characteristics (surface-specific electrical contact resistance < 20 mΩ*cm² at 16 bar) and very good corrosion resistance under the typical conditions of a polymer electrolyte membrane (PEM) fuel cell (corrosion current density < 10⁻⁶ A/cm² at +0.9 V_{SHE} (with reference to the standard hydrogen elec-

trode SHE)). They therefore meet the requirements defined by the US Department of Energy (DOE) for metallic bipolar plates in automotive fuel cells.

Plasma-supported optimization of the advanced prototype components and welding of the bipolar plates are carried out in cooperation with a university and a Fraunhofer Institute from the fields of surface refinement and joining technology. ThyssenKrupp is assessing the desired optimization of contact resistance and corrosion resistance in extensive studies and is thus pushing development forwards. Advanced prototype component design, forming and trimming are undertaken by ThyssenKrupp together with a forming technology partner. Previously plasma-modified bipolar half plates have been successfully formed without visible defects as part of these tests. This is an important prerequisite for a continuous process on a pilot scale.



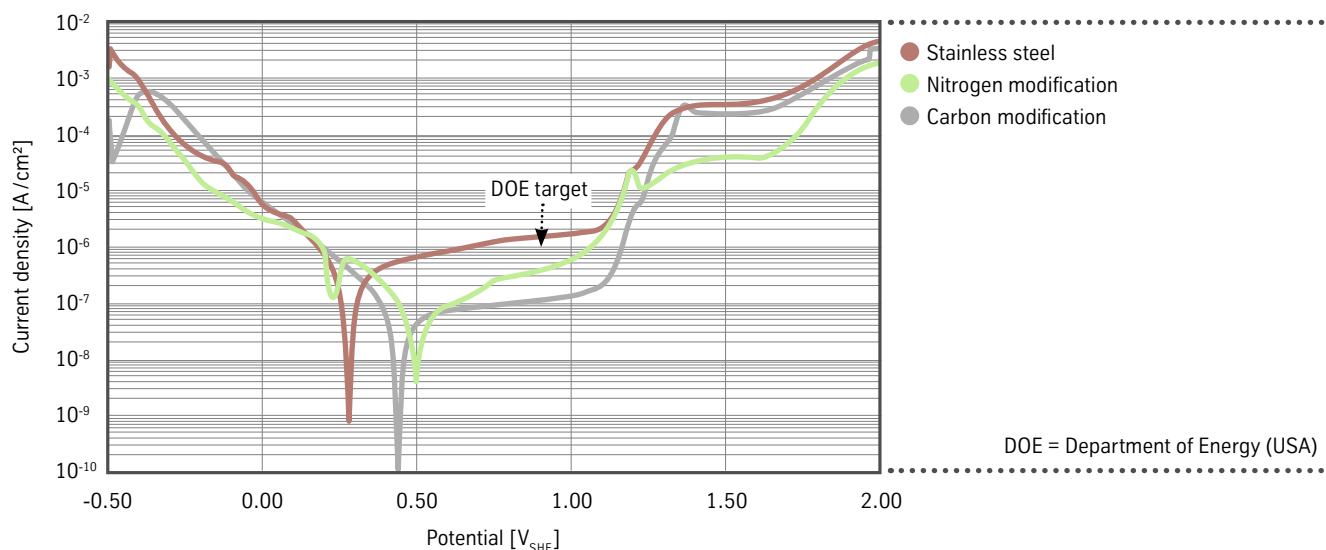
③ Bipolar plates with different surface modification



④ Measurement of electrical contact resistance depending on contact pressure

TESTED UNDER REAL OPERATING CONDITIONS

Before further processing, the surface-modified stainless steel runs through typical application tests to check its usability in an automotive fuel cell. The most important criteria are electrical contact resistance and corrosion resistance in diluted sulfuric acid under real operating conditions. When measuring electrical contact resistance, the surface-specific contact resistance is determined as a function of the contact pressure, ④. The stainless steel modified with carbon and nitrogen reveals resistance values which are approximately identical to those of the gold-coated reference sample. Contact resistance is 30 times better than that of untreated stainless steel 1.4404. This significant



5 Current density potential measurement in diluted sulfuric acid, potential increase speed 0.5 mV/s

improvement is necessary to minimize electrical power output losses within a fuel cell stack. Minimization of such losses caused by heat is particularly important to keep the need for weight- and space-intensive cooling low and maximize the efficiency of a fuel cell drive system.

To obtain a more precise assessment of corrosion resistance, the modified stainless steel is subjected to an electrochemical stress test with diluted sulfuric acid under oxygen. 5 shows the result of the subsequent current density potential measurement. In the typical operating range of a fuel cell, the stainless steel modified with nitrogen and carbon behaves significantly better than the untreated reference. This improvement is also vital so that the surface of the bipolar plate withstands the risk of corrosion in mobile fuel cell operation.

The surface-modified bipolar stainless steel plates which were investigated already meet the DOE's development

objectives for automotive fuel cells in terms of corrosion and contact resistance, 6.

OUTLOOK

With this advanced prototype component of a bipolar stainless steel plate, ThyssenKrupp has developed a cost-efficient solution in comparison with the gold-coated reference together with its partners. It already meets important requirements for use in a PEM fuel cell in automobiles. This is an excellent starting point for future process development whose suitability in fuel cell stacks still has to be proved in further development and optimization work. Above all, however, there is a need to design an economic industrial manufacturing process. In comparison with the process solutions available so far, there is a good likelihood of manufacturing bipolar plates in an efficient, continuous production process.

	Electrical contact resistance [mΩ x cm²] at 16 bar	Corrosion current density with dynamic corrosion stress at 0.9 V _{SHE} [A/cm²]
DOE 2015 target	20	< 1.0 x 10 ⁻⁶
1.4404 uncoated	500	< 1.5 x 10 ⁻⁶
1.4404 + carbon modification	16	< 0.1 x 10 ⁻⁶
1.4404 + nitrogen modification	18	< 0.5 x 10 ⁻⁶

6 Comparison of the characteristics of the advanced prototype components with the DOE target values

CHASSI

The background of the entire page is a dark, almost black, field. Overlaid on this is a pattern of bright green, oval-shaped dots. These dots are arranged in a grid-like fashion, but the grid is not perfectly uniform. Some areas have denser clusters of dots, while others are more sparse. The dots appear to be slightly blurred or have a soft glow, giving the pattern a sense of depth and movement. The overall effect is reminiscent of a digital or scientific visualization, perhaps representing a network or a microscopic structure.

& STE

S



Electrically assisted steering systems are both the ticket into the world of partially or fully autonomous driving and also reduce fuel consumption in comparison with conventional hydraulic steering systems. In the InCar plus chassis and steering subproject, the ThyssenKrupp engineers' objective is therefore to make electrically assisted steering systems more efficient and design them for new vehicle classes. The multi-material design of damper tubes and steering components is a further development focus. In addition to innovative product solutions, appropriate manufacturing and assembly processes are also available for implementing this in large-scale production.

ERING

MORE EFFICIENT CHASSIS PARTS

Ultra light and cost-optimized damper tubes, lighter and even more compact vehicle springs plus a new, integrated variable damping system: these are just some of the innovations with which ThyssenKrupp is achieving increased vehicle component efficiency and performance. Today, OEMs expect to be able to integrate these components into increasingly complex systems. In addition to lightweight design and function optimization, development activities are therefore also focused on optimal package design and compatibility with active, networked chassis systems.

SAVING WEIGHT AND SPACE WITH THERMOTECWIRE

Vehicle suspension springs manufactured from ThermoTecWire are almost 20 % lighter than previous suspension springs and therefore make an outstanding contribution to lightweight design in the chassis. The package is also optimized in addition to the consumption and emission advantage, as the spring produced using the innovative spring wire is considerably shorter than before – and all of this without any reduction in performance despite the increased stress on the spring material. Lightweight suspension spring design is supported by the newly developed ElastoProtect surface coating, which effectively protects the spring surface from damage even under harsh environmental conditions.

Thanks to thermomechanical forming – called the ThermoTecProcess – the familiar and established ThermoTecSpring suspension springs are up to 15 % lighter than conventional springs and attain the same service life as these. Within InCar plus, ThyssenKrupp is now consistently further developing the ThermoTecProcess and introducing ThermoTecWire, a new spring wire with improved characteristics. The ThermoTecSpring manufactured using the new spring wire is a further 3 % lighter than the first generation of suspension springs and up to 20 % lighter than conventional suspension springs. The ThermoTecSpring with spring wire made from ThermoTecWire also offers a package advantage which can be implemented either through the length of the spring or the diameter of the spring body.

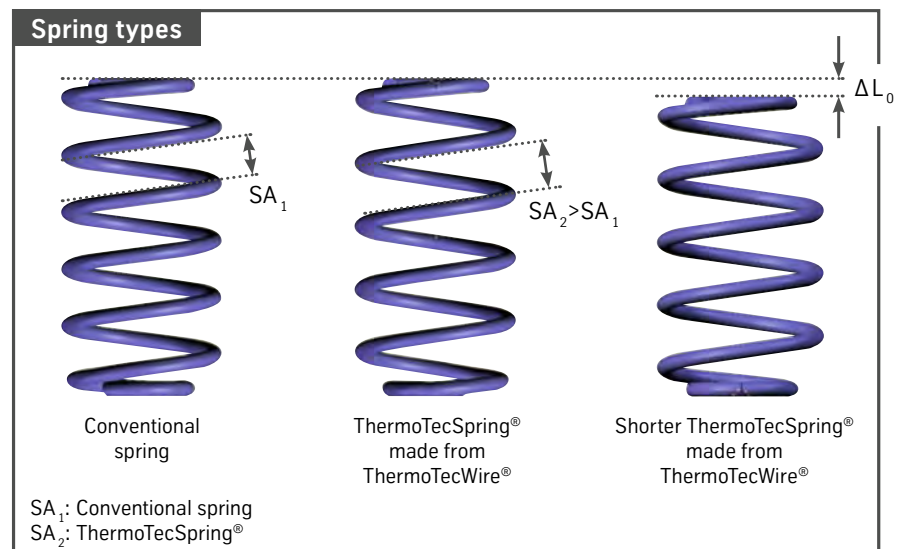
Suspension springs are highly stressed, weight-optimized components. Each further weight reduction is based on optimization of the spring material in terms of the bearable stresses when subjected to static and dynamic loads. To enable the spring to withstand higher stresses, the material's strength has to be increased without affecting its toughness. Such an improved material enables coil springs with a smaller wire diameter and fewer coils with an unchanged service life, ①.

SEPARATE PROCESS FOR EVEN GREATER TOUGHNESS

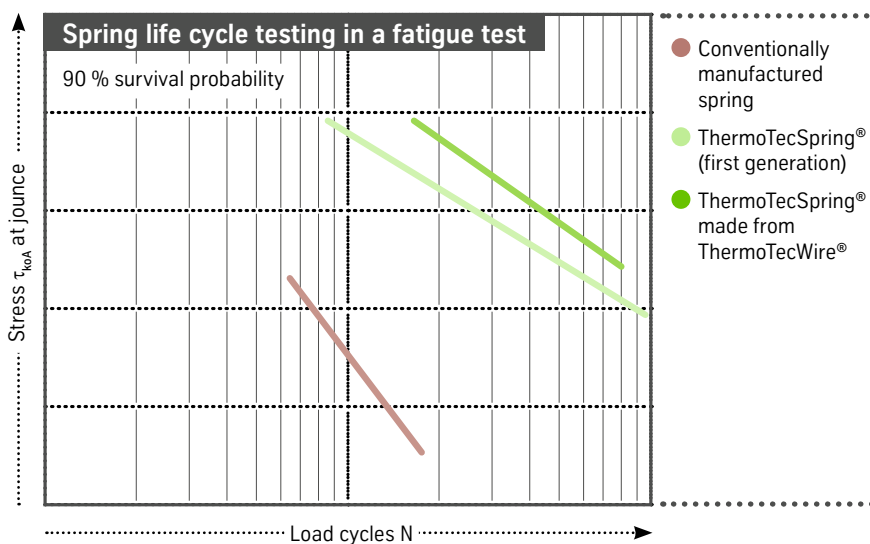
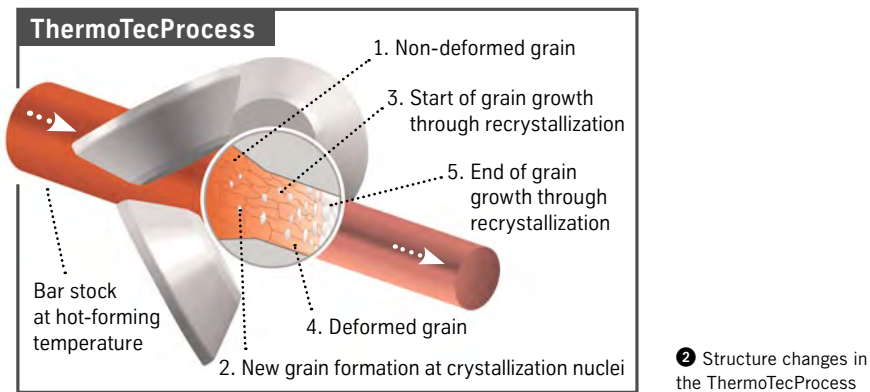
ThermoTecWire is the name given by ThyssenKrupp to spring steel whose toughness is increased through thermomechanical forming. This forming process is a combination of mechanical forming and defined heat control of the spring wire. Temperature- and time-dependent recrystallization processes in the material lead to the formation of a finer structure during and after forming, ②. This effect

occurs after exceeding a critical forming level. The finer grained structure and the related increase in toughness enable strengths of up to 2200 MPa in the material – without service life disadvantages. 1900 to 2050 MPa are standard at present.

The thermomechanical treatment used for previous ThermoTecSpring suspension springs consists of a single-stage rolling process between heating and winding the spring wire. With ThermoTecWire, this additional manufacturing



① Lightweight springs with ThermoTecWire in comparison with a conventional spring



③ ThermoTecWire springs have a longer service life

step is now undertaken separately on the input material. The effect on the structure is actually improved due to the changed process sequence. Fatigue tests prove that the service life of springs manufactured from ThermoTecWire is additionally extended, ③.

With a consistently lightweight-oriented spring design, this extended service life can be transformed into a weight saving of up to 20 % in comparison with a conventional spring. Added to this is the package gain shown in ①. Specific values are dependent on the individual case. Boundary conditions such as the characteristic curve, the package, lateral force compensation, the installation situation and the service life exert an influence. The spring's robustness can, of course, also be improved with ThermoTecWire without exploiting the weight potential.

The reduced amount of material required has a particularly positive impact on the cost side. However, additional costs are incurred due to the separate thermomechanical treatment. Again the lightweight design costs are extensively dependent on the individual case here. Cost neutrality tends to be anticipated more with increasing spring weight, as the volume of material saved in absolute terms then increases.

One further advantage of the new process is its broad application scope. Whereas the first generation ThermoTecSpring is limited to hot-formed coil springs with cylindrical wire, the ThermoTecWire spring wire is suitable for all wire geometries including wires with conical ends. The objective of further development work is use of the innovative spring wire for all coil springs, irrespective of manufacturing process and spring geometry.

INNOVATIVE SURFACE PROTECTION

However, the increased material strength and permissible stress make the spring steel more sensitive to damage in the surface area. Particularly in combination with corrosion, this can basically lead to crack formation, because the highest stress loads occur at the surface and in the surface-near areas of the wire cross-section. As the spring may be exposed to adverse and changing environmental conditions such as stone impact, moisture or road salt depending on the area of operation, protection of the spring surface is important.

To achieve this, ThyssenKrupp is developing a new paint called ElastoProtect. This single-layer coating consists of a modified epoxy powder paint with increased energy absorption capacity which prevents particles from penetrating through to the spring steel. No paint delamination occurs even under extreme conditions such as the cold impact test at -40 °C, ④.

ElastoProtect therefore protects the spring more effectively against mechanical surface damage than the present thin powder coatings. Unlike modern two-layer coatings, ElastoProtect also requires no additional zinc layer (primer). ThermoTecWire springs and the new ElastoProtect paint will shortly be available at ThyssenKrupp plants around the world.



④ Impact crater without paint delamination

FUNCTION-OPTIMIZED DAMPER TUBES

ThyssenKrupp has developed new damper tubes for individual package requirements, tailor-welded variants with optimal costs and functions plus an optimized lightweight version. For example, the damper tube manufactured from carbon fiber reinforced plastic (CFRP) is up to 45 % lighter than an aluminum damper tube. Newly developed stainless steel tubes offer increased corrosion resistance for mono- and twin-tube dampers. Certain solutions can be implemented directly in volume production.

Dampers positioned between the exhaust system and brake are subject to very high thermal stresses. To better dissipate the heat which builds up due to post-heating after switching off the engine or heat from the brakes while stationary, the dampers must have a larger oil volume or a larger tube surface. A permanent sealing function cannot otherwise be guaranteed.

T³ DAMPER TUBE WITH INDIVIDUAL PACKAGE

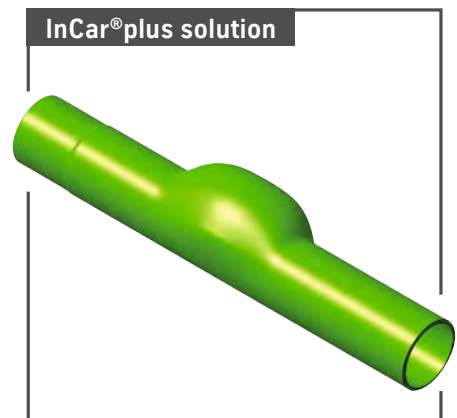
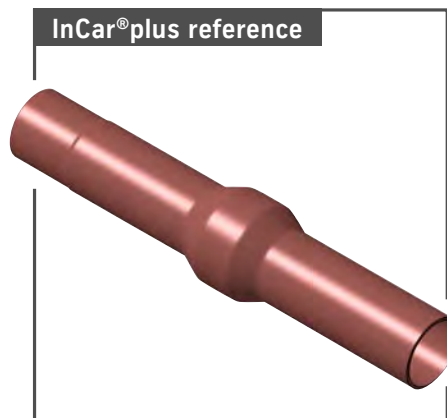
In the reference tube, this larger surface has been achieved through a convexity, ❶ (left). To do this, the tube is expanded in a multi-stage forming process and then constricted again. ThyssenKrupp has developed a solution with optimized functions and costs for this special package, ❷ (right).

The tube is produced as a stamped and formed part in an innovative manufacturing process called T³ technology. In many cases, this manufacturing process enables the integration of functions into a restricted package, which is not possible with the conventional manufacturing technology. The tube can be specifically formed and adapted to the package in each area. The direct integration of tube constrictions in the upper area is also possible to enable the use of standard components for mounting the tube. Depending on the geometry and the loads to be transferred, the spring seat can also be integrated directly into the tube.

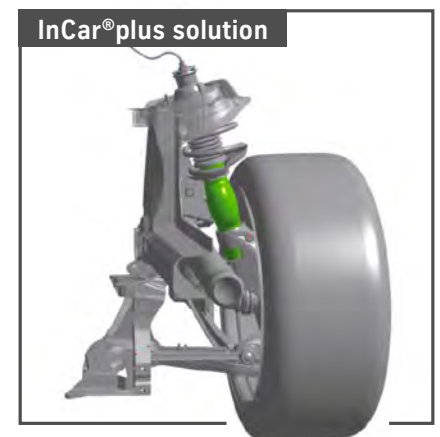
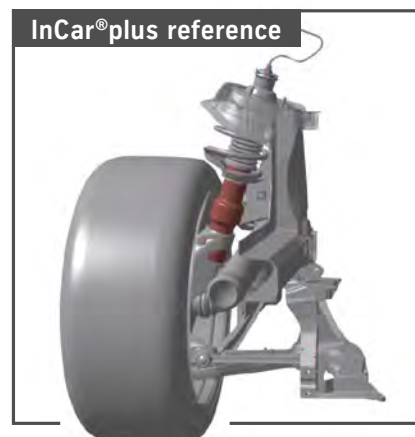
Radial expansion of the reference tube is severely limited by the wheel carrier

and the rim, ❷ (left). The T³ tube is not subject to this package conflict, as the additional volume can be optimally positioned in consideration of the package situation, ❷ (right).

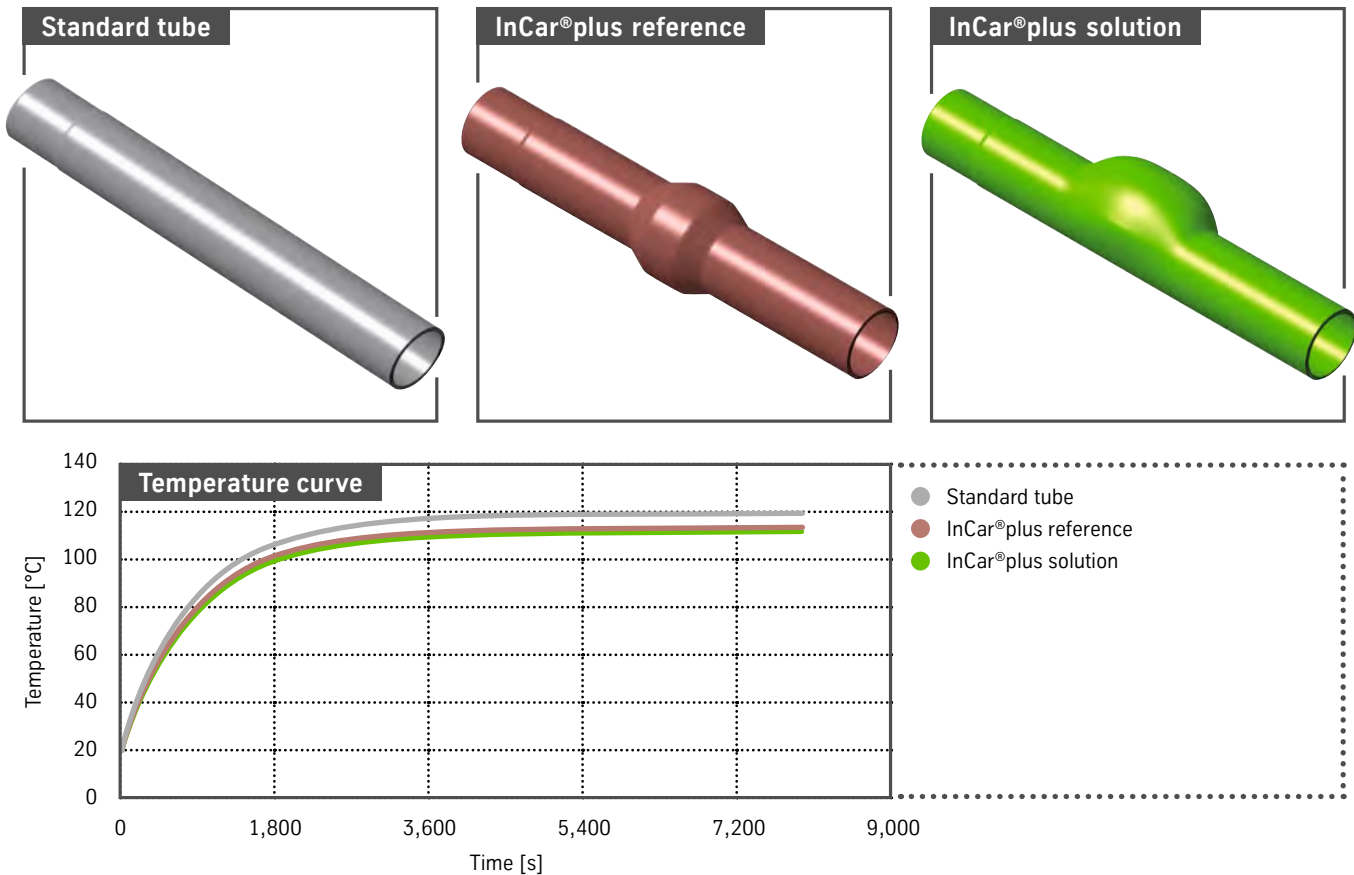
In addition, the wall thicknesses should remain as constant as possible during forming in order not to weaken the component. The switch from classic tube drawing to the T³ component enables the



❶ InCar plus reference tube (left) and InCar plus T³ damper tube (right)



❷ Schematic installation of the reference damper tube (left) and the T³ damper tube (right)



③ Comparison of tube variant thermal simulation

avoidance of material thinning at critically stressed points, e.g. directly above the wheel carrier. The damper tube can therefore withstand at least the same temperature level as the reference tube, but with considerably greater design freedom. This is backed up by extensive simulations, which actually reveal slightly better heat dissipation in comparison with the production design, ③.

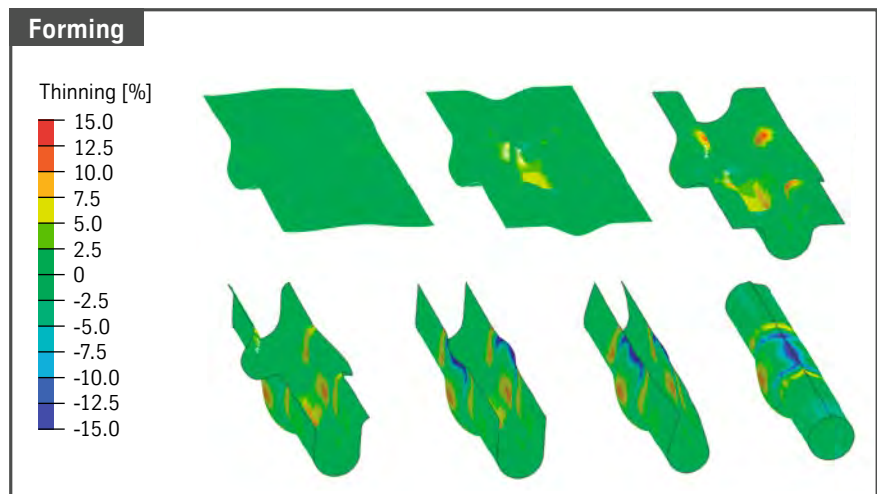
The increase in the size of the surface and the oil volume must be accompanied by adherence to certain component characteristics such as roundness, diameter and weld seam quality in the clamping area. These characteristics are required for smooth assembly of the seal guide unit and mounting in the wheel carrier, and can be achieved very well with the T³ technology. In simplified terms, the tube is sealed using laser-aided longitudinal seam welding after the forming process in this technology.

Prior to initial prototype manufacturing, the first pre-cut blank part is determined in a simulation. In accompani-

ment, U-shaped profile edge forming is optimized to generate a process-consistent and laser-friendly butt joint for the weld seam, ④. The tube seam is then longitudinally welded with a laser – without filler metal and with controlled seam sinkage on the inner and outer side to

ensure that it can be installed in the wheel carrier. The weld seam quality produced in this process enables a permanent and leak-tight damper seal by means of rolled closure after forming.

In subsequent project steps, ThyssenKrupp investigated all further



④ T³ technology forming simulation

processes for manufacturing a ready-to-install damper tube. This includes e.g. welding on the bottom section and spring plate, assembling the damping unit as well as sealing and painting the damper tube. Static and dynamic tests are then undertaken to validate durability and leak tightness.

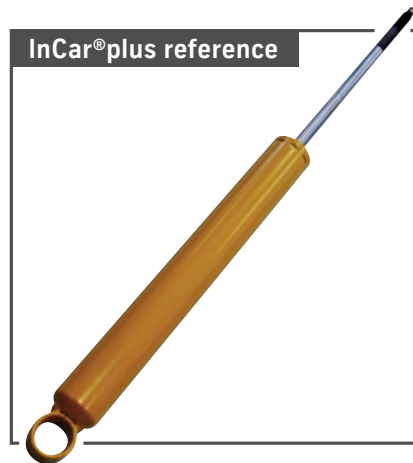
Besides the classic draw-out and tear-off tests for the rolled closure and the spring plate, durability of the entire suspension strut is investigated in various dynamic stress tests. A pressure sensor in the tube permanently monitors leak tightness and immediately registers leaks in the event of weld seam failure. The spring plate weld seam and the rolled closure are tested by inducing an increasing load. Functional verification in the assembly is guaranteed by a module endurance test in which a recorded load spectrum is applied to the complete suspension strut module.

STAINLESS STEEL DAMPER TUBE

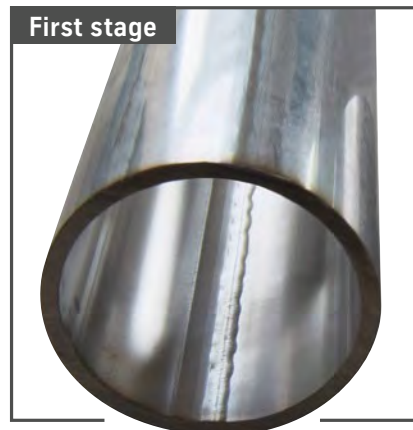
One other InCarplus project solution is dealing with the development of a corrosion-free damper tube. It is intended to meet all future requirements and withstand even difficult boundary conditions such as poor road conditions, off-road use and an increased risk of corrosion due to road salt. The stainless steel solution developed for this is equally suitable for both mono- and twin-tube applications.

The reference tube, ⑤ (left), is painted in classic form with dip painting or electrostatic spray painting. These standard processes are increasingly encountering their limits due to rising corrosion protection requirements. The desired, global use of common parts and processes is now only ensured to a limited extent. In countries with extreme climatic conditions such as Russia or China, significant additional effort has to be undertaken to meet these requirements. In certain cases, for example, weld seams have to be brushed before painting, paint shadows ruled out through laborious pre-painting and certain inaccessible areas which are susceptible to corrosion have to be subsequently waxed.

These cost-intensive, additional processes are not necessary with the InCarplus solution, ⑥ (right), as stainless steel is corrosion-free and also offers an attractive visual appearance. The lat-



⑤ Painted (left) and stainless steel damper tube (right)



⑥ View of the stainless steel tube after various drawing phases

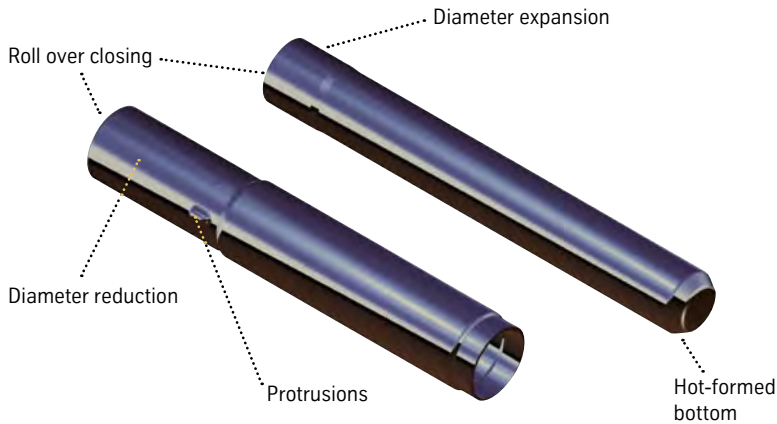
ter plays a significant role, particularly on off-road vehicles and pick-ups, as the damper is usually directly visible on these. Special vehicle series with particularly high corrosion protection requirements are another area in which stainless steel damper tubes could conceivably be used.

The stainless steel tubes additionally have to demonstrate the leak tightness and surface quality required for mono-tube applications. This leads to very tight diameter tolerances. Corresponding prototypes are being developed together with a tube manufacturer specialized in stainless steel on the basis of a 36 mm diameter standard damper tube, ⑥. The challenge involved in this is to completely eliminate the weld seam through drawing processes. To do this, the tube has to be manufactured in several stages until the required accuracy is attained.

An austenitic stainless steel is most suitable for this. Its mechanical values

correspond to those of the standard carbon steel tubes used today. The tube is validated with standard FEM calculations. To do this, buckling and tensile loads are introduced into the tube assembly, with differing wall thicknesses and tube bottoms. The damper closure is also assessed. These tubes' limited offset yield stress is due to the high expansion of the material. This has no bearing on the strength of the tube.

Initial manufacturing tests show that a welded-in bottom reveals better characteristics than a standard, hot-formed bottom. The tube bottom consists of the same material as the tube and is joined to the tube by means of laser welding without filler metal. The lower connection for mounting the bearing and the weld seam are also manufactured from stainless steel. As in the reference, the sealing package located in the upper area of the damper is equipped with an aluminum guide body. The housing

Damper tubes

7 Tailor-welded tubes

therefore had to be hard anodized to combat the contact corrosion which occurs with this material pairing. This type of coating has proved suitable at ThyssenKrupp over a number of years.

During testing, the tubes successfully completed a 240-hour salt spray test without any signs of corrosion. The tensile tests revealed results similar to

those of the reference. In the sine-on-sine endurance test, the fully assembled damper is subjected to a long-term test. A double eccentric machine executes one million basic strokes and twelve million overlapped short strokes. As well as the classic durability tests, function tests are also performed with the stainless steel tube. In these tests, static

and dynamic friction between the inner wall of the tube and the valve system's guide/sealing ring are investigated. The low-temperature leak tightness and high-temperature suitability of the static guide seal to the stainless steel tube are also evaluated after a corrosion endurance test.

This solution can be implemented on short notice for volume production without major effort and is suitable for all dampers. In addition, subsequent use in suspension struts with add-on parts is also feasible.

TAILOR-WELDED DAMPER TUBE

ThyssenKrupp is studying tailor-welded damper tubes in combination with all conventional tube forming operations for new twin-tube damper solutions. This product cost-driven environment raises the question of conditions and possibilities for the use of less expensive tubes.

Various tests show that such damper tubes can be manufactured cost-effectively and that their high level of maturity supports use in production, 7. In comparison with the reference damper tube, a drawn component, the additional drawing processes are omitted in the

Hot-formed tube

8 Various hot-forming process stages

case of tailor-welded tubes. The focus here is on the longitudinal weld seam. In contrast to drawn reference tubes, this is merely scraped and therefore reveals a slight depression. The weld seam and subsequent annealing must be precisely defined to avoid cracks and leaks in all forming operations.

Due to different customer requirements, ThyssenKrupp undertakes a number of different forming operations on the tubes. As a rule, the stiffness, package and durability requirements dictate certain tube diameters and wall thicknesses in advance. To avoid generating special solutions for standard components, e.g. the sealing and guide units plus jounce caps, the diameter is often widened and constricted. In certain cases, the lower end of the damper is also constricted to improve installation in clamped wheel carriers or to place the tube on the drawn-in edge in the wheel carrier (vertical stop).

Spring seats are also placed on tube constrictions. In order to mount the spring seats in the correct position and secure them against rotating, an additional protrusion is formed in the tube. It must be ensured in this case that this massive forming in a very tight space does not damage the weld seam. To do this, ThyssenKrupp has undertaken extensive tests and produced ground material sections.

One important characteristic is the tailor-welded tubes' unreserved suitability for the hot-forming process. During hot-forming, the tube is heated inductively and pressed into a mold with a rotary movement until the end of the tube is completely sealed and gas-tight. This was verified by several test pieces manufactured under near-production conditions, ⑧.

The suitability of the tailor-welded tubes for radial and axial standard seal systems has also been proven. Defined weld seam scraping enables permanent sealing of the damper at the sealing point between the reservoir tube and guide. In both axial and radial seal guide systems, the elasticity of the sealing material is sufficient to fill the tube's scraped weld seam indentation. Endurance and low-temperature leak tests prove that this technique functions reliably over the entire temperature range of a twin-tube damper from -40 to 80 °C (temporarily up to +120 °C).

InCar plus solution



⑨ Sectional view of the ultra lightweight damper

WEIGHT-OPTIMIZED CFRP DAMPER TUBE

The "ultra lightweight damper tube" is a further development in the InCar plus project. In this, development is focused on maximum weight reduction in a mono-tube damper and the technical feasibility of CFRP structures. The current prototype is 33 to 45 % lighter than a standard damper tube in lightweight aluminum design. Firstly, this damper tube has no metallic function or running surface and is therefore very light. Secondly, the low density and high strength of the carbon fibers, together with load-specific fiber orientation, ensure a very stiff and nevertheless light tube. In this prototype, the fibers are located radially and axially in alternating angular positions to the damper axis to cope with the load. Particular attention in this case is paid to the load bearing elements, which have to guarantee fiber-friendly introduction of the operating loads into the tube structure.

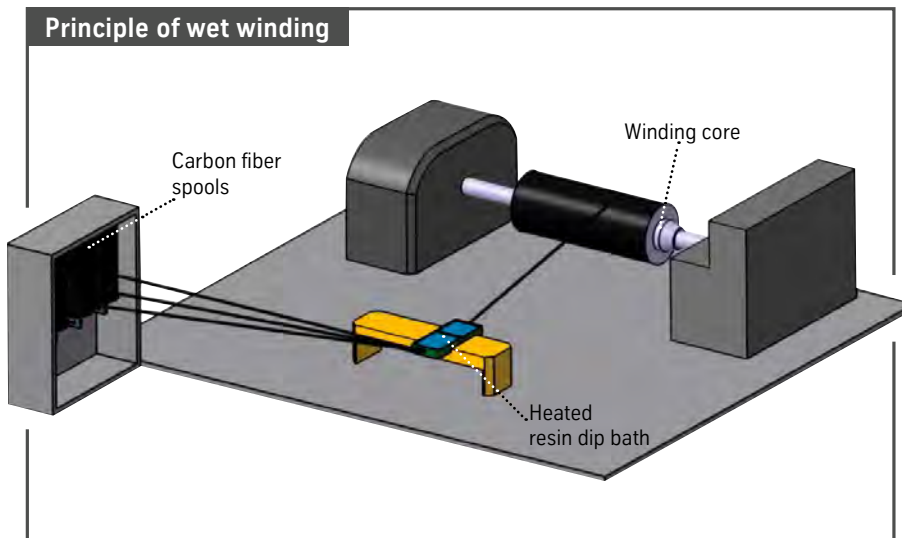
In addition to the mechanical stress (with dynamic operating loads of ± 30 kN in this case), the thermal component stress plays a particularly major role in the choice of material. The mono-tube damper operating temperatures of -35 °C to over 160 °C which are possible in reality make high demands on the composite consisting of a matrix, inlay and fibers. The low thermal conductivity of the fiber composite material poses an

additional difficulty, as it results in a significant difference between the externally measurable and the actual internal temperature of the tube. Wall thickness minimization, which is desired in any case, helps to protect the inner components against overheating and to minimize the temperature difference.

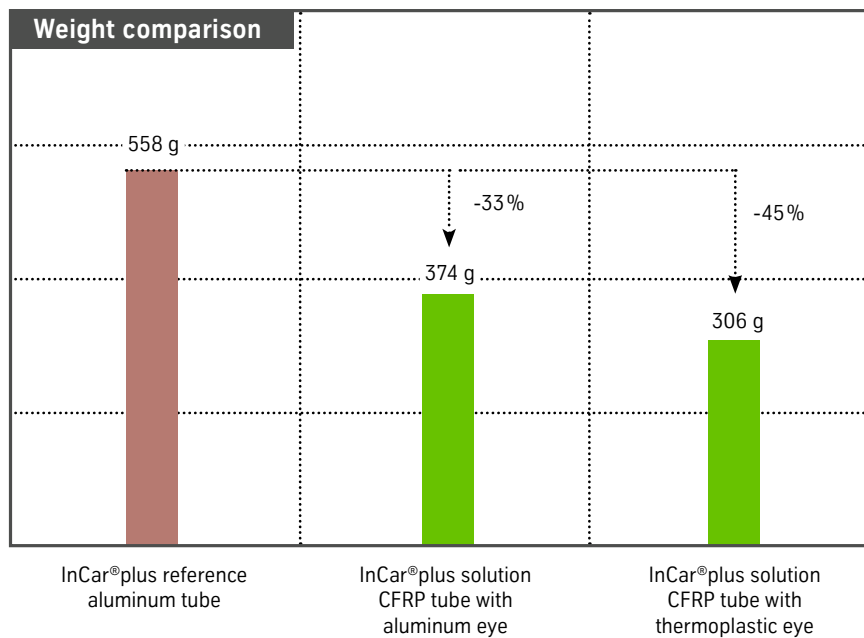
In contrast to a mono-tube damper, sealing against the inner tube surface is undertaken below the load bearing elements so that the system remains leak tight even in the event of severe temperature fluctuations and the different thermal expansion coefficients of the load bearing elements and the CFRP tube, ⑨.

The fundamental suitability of the different CFRP material and connection concepts was already proven back in 2012 on component and damper endurance test rigs. ThyssenKrupp's CFRP experts then developed an industrialization concept which is fit for volume production.

At present, the damper tubes are manufactured using the wet winding process, ⑩. "Filament winding" is a conventional process in which the carbon fibers are integrated into the component without semi-finished product manufacturing and the matrix system is simultaneously fed into the process on-line. The intermediate step of preforms, prepregs or semi-finished products is omitted. The fibers are unwound from the reels and guided through a temperature-controlled resin bath. The resin



⑩ From reel to tube: schematic representation of the winding process



⑪ Comparison of the CFRP solutions with the aluminum reference

content in the fibers can be adjusted to the desired amount.

Controlled by CNC, the soaked fibers are then deposited on the winding core with defined tension. In this process, the load bearing elements are positioned on the core in advance and integrated into the carbon fiber laminate using the wet winding process. After matrix hardening and tempering, the core is removed from the finished tubes. The surface quality of the core and the previously applied substances is coordinated such that the desired sealing and function surface is available directly after hardening.

The CFRP damper tube, including the lower connection and the connection option for the sealing packaging, is integrated into the weight balance. As all of the other components are identical to the aluminum reference, the ascertained weight difference applies to the entire damper. The comparable aluminum tube weighs a total of 558 g, the CFRP tube 374 g. The weight saving is therefore 184 g or 33 % per damper tube, ⑩.

If the CFRP tube is further optimized, this weight advantage will be even higher in the future. At present, work is

being undertaken to integrate the lower aluminum boss connection and on a connection manufactured from a glass fiber-filled plastic (thermoplastic boss). Initial tests indicate that further weight can be saved in this way. In comparison with the aluminum reference, the CFRP damper tube would then be 45 % lighter. Testing of the CFRP damper tube with aluminum boss connection on the test rig has already been completed. Initial damper prototypes are undergoing test drives at an OEM and have already successfully completed several tens of thousands of kilometers.

VARIABLE DAMPING SYSTEM FOR INCREASED RIDE COMFORT AND AGILITY

The new, integrated variable damping system from ThyssenKrupp extends the variable damper portfolio with an infinitely variable, fast switching, pilot-controlled pressure relief valve. The wide damping force range in the rebound and compression stage as well as the high adjustment dynamics resolve the conflicting aims of ride comfort, driving safety and agility even better. A pilot valve actuated with a magnet precisely controls the pressure for the two independent main valves for the rebound and compression stage. This approach also enables a wide range between the soft and hard characteristic in the compression stage.

Variable damping systems are now available in compact class vehicles and offer drivers better ride comfort with increased agility and driving safety at the same time. To achieve this, the chassis control system's control unit can individually adapt the damping forces for each wheel in a few milliseconds using data from the acceleration and travel sensors, etc. A corresponding control strategy keeps disturbing road excitations away from passengers as far as possible and simultaneously actuates the dampers so that body movements are stabilized as well as possible. To optimally meet the different requirements of various vehicles and OEMs, both piston-integrated control valves (valve is located at the end of the piston rod within the damper) and control valves mounted on the outer damping tube are used, ❶.

PILOT-CONTROLLED PRESSURE RELIEF VALVE

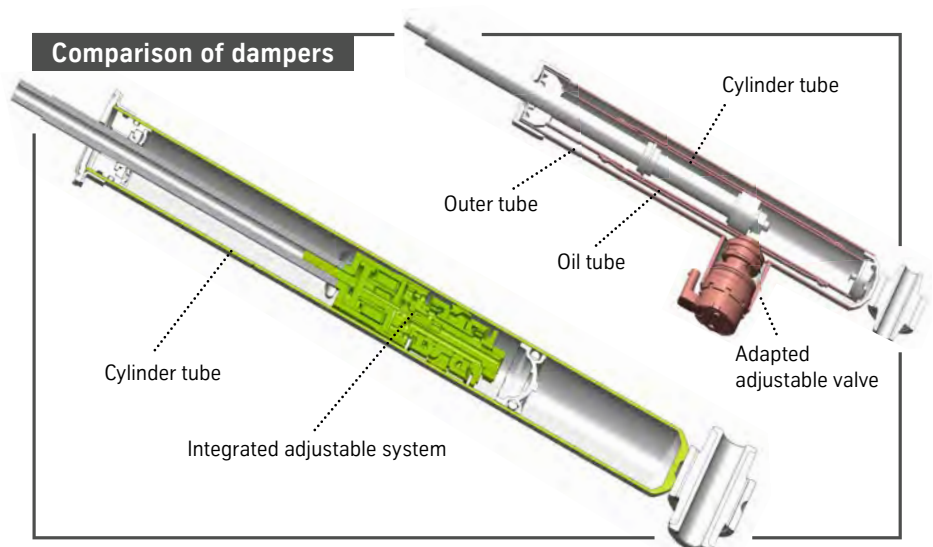
In InCar plus, ThyssenKrupp has developed a new, infinitely adjustable damping valve. A control valve integrated into the piston offers significant potential for reducing the weight of the damper in comparison with the outer tube solution. Firstly, the oil guide tube required to channel from the damper's working

chambers to the external valve is omitted; secondly, the inner tube of a twin-tube damper is no longer required if the valve in the mono-tube damper is used. Both ensure a weight reduction of up to 600 g as against comparable dampers.

With its compact dimensions, the proportional control valve is suitable for use in tubes as of an inner diameter of 36 mm. This enables integration into a variety of McPherson struts. A variant

with a diameter of 40 mm is available for a higher damping force level, which is often required for unfavorably linked dampers. Due to the control valves' modular principle, both variants only have a few different parts. Thanks to high functional integration, the length of the valve is less than 100 mm, as a result of which it can be used in numerous axle concepts.

Before defining the control principle, ThyssenKrupp discussed the specific



❶ Comparison of a piston-integrated control valve (left) with a control valve mounted on the outer tube (right)

weighting of individual functional characteristics with the OEMs in workshops. The map design, switching time and controllability requirements which were determined led to the development of a pilot-controlled pressure relief valve. This control principle preferably enables the generation of a damping force map in which the damping force is independent of the damper speed due to very flat pressure limiting gradients over wide ranges, ②.

This behavior is reflected in extensively linear damping force-current behavior and significantly facilitates regulation of the proportional control system. One other important require-

ment which the new valve meets is the wide pressure stage force spread. As the pilot control principle is also applied in the pressure stage, low damping forces are possible in the soft characteristic and high damping forces in the hard characteristic.

PILOT STAGE CONTROLS MAIN STAGES

Depending on electrical current, the magnetic force-actuated pilot stage controls the pressure for the main stages, ③. Several challenges have to be resolved on use of this valve principle in the damper. In the vehicle, the damper

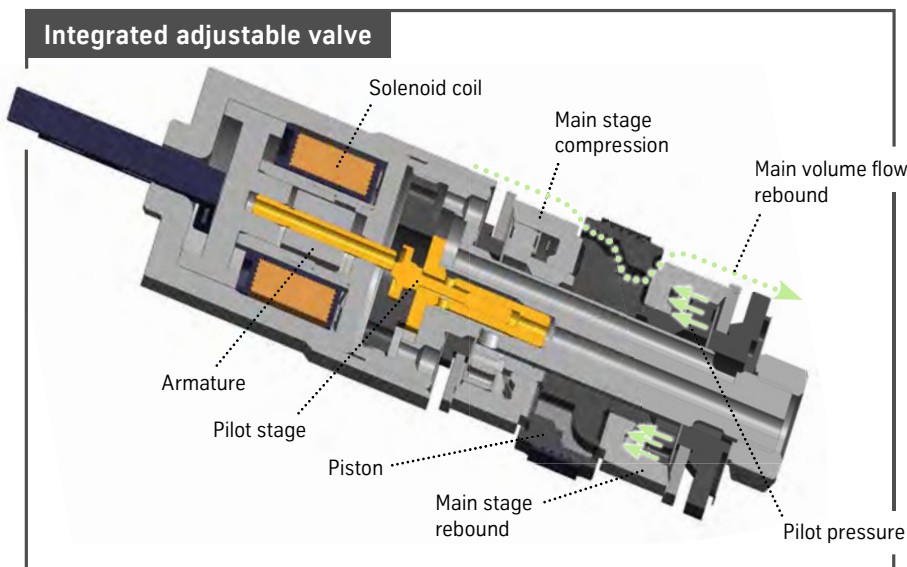
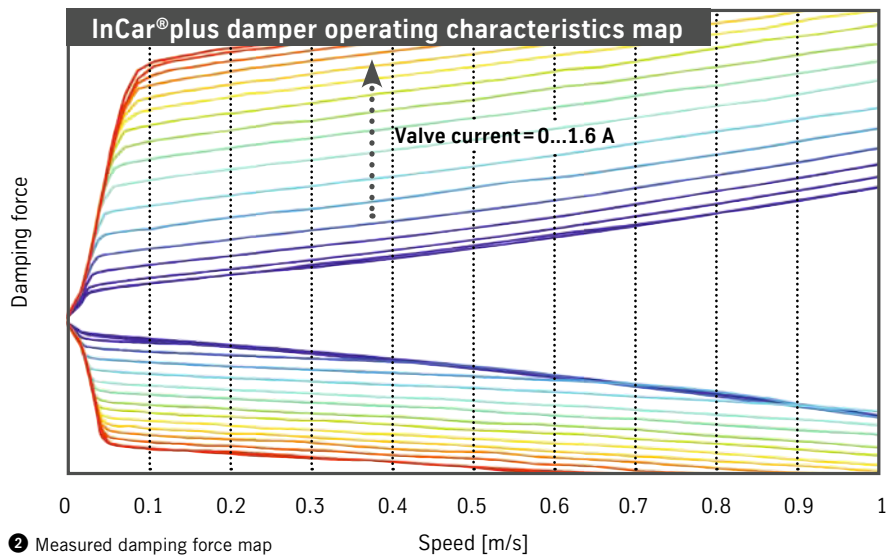
moves in both the rebound and compression direction. This means that the damper oil flows through the valve integrated into the piston on alternate sides. As a common pilot stage is available for both directions but is only effective on one side, the volumetric flow has to be rectified. This is undertaken by check valves in the form of spring loaded or clamped shim valves. With their low masses and large pressurized surfaces, both designs offer the required high switching dynamics. As there is no external pressure supply and the pilot stage is supplied with pressure generated by the damper itself, this function must also be guaranteed at lower pressure. This is the case during operation in the soft characteristic or at low excitation speed.

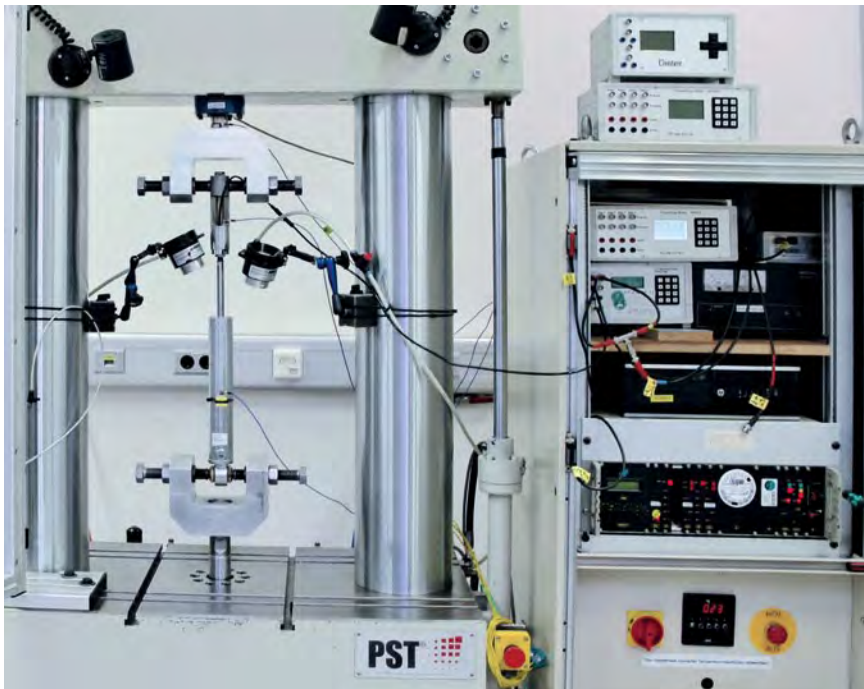
To minimize the system's energy consumption, the proportional magnet is designed such that it exercises no force on the pilot stage in currentless condition. The damper is therefore in the soft characteristic. During vehicle operation, the damper is primarily operated in the low damping force range and thus at low current, e.g. during smooth travel over a relatively level road surface. Low damping forces then ensure good superstructure insulation against road surface excitation. High damping forces, e.g. to stabilize the superstructure during dynamic driving maneuvers, are only set temporarily. At maximum damping force, a valve current of 1.6 A flows, leading to maximum power output loss of 13 W. An electrical power output loss of approximately 2 W per damper arises depending on road surface condition and the vehicle dynamics requirements.

An optional failsafe function can be implemented in the control valve; in the event of an electrical fault, it sets a firmly defined mean damping force characteristic. In currentless condition, which, for example, could arise due to a line defect, an additional, passive pressure relief valve regulates the pilot stage pressure for the rebound and compression stage.

REBOUND AND COMPRESSION STAGE EXTENSIVELY INDEPENDENT

The main stages are defined as pressure chambers, which the pressure regulated by the pilot valve reaches via channels. Via the precisely dimensioned, pressurized surfaces, the pressure leads to





4 Function and lifetime testing

defined pre-tensioning of the main stage pistons on the valve seats. The main valves remain closed until the damping pressure on the opening surfaces exceeds the pre-tension. Only then do the main valves for the rebound and compression stage assume their pressure control function.

The valve's stable function is based on corresponding coordination of surface ratios, inflow and outflow resistances and further important valve characteristics. Special requirements arise for the valve's soft characteristic. To achieve good disturbing force insulation from the body, the damping forces should be as low as possible. A variable soft characteristic is required to enable a response to specific events such as wheel imbalance even without controller intervention. Large flow cross-sections and sufficient main stage lift travel ensure the soft damping characteristic potential. The characteristic is set using an adjustable disc spring package and is therefore based on the tried-and-tested setup of conventional dampers.

Hydraulically, the piston-integrated control valve design offers the advantage that the rebound and compression stage can be designed very independently. This is a major advantage, particularly in the case of the soft characteristic, in comparison with twin-tube

dampers which operate according to the uni-flow or re-pumper principle with an adapted valve.

The innovative InCar plus piston-integrated control valve is predestined for use in mono-tube dampers. It offers the option of adapting the ratio of maximum rebound to maximum compression stage force to the vehicle setup over wide ranges. However, these characteristics also enable high setup flexibility under hydraulically restrictive boundary conditions in twin-tube dampers and McPherson struts.

In addition to extensive testing on the test rig, 4, the valve is already undergo-

ing successful testing in various concept vehicles, 5. Valve actuation is also adapted to exploit the advantage of the high adjustment potential and the system's high control dynamics. To achieve this, ThyssenKrupp is continuing to extensively develop its own chassis controller. This is already fitted as standard in various vehicles. The interaction between the control valve and damper regulation offers the driver noticeably more ride comfort and agility.

The advanced development status of this damper system is laying the foundation for rapid production development in cooperation with the OEM.



5 Testing in the concept vehicle



STEERING MADE EASY

Cost-effective weight reductions of up to 60 % in steering components! This is particularly noteworthy, because a vast range of easily accessed lightweight potential has already been exhausted. Added to this is the fact that the next generation of electrified steering systems offers significantly extended implementation options. However, these are by no means the only advantages of ThyssenKrupp's steering system innovations. Multi-material design components, new technologies for steering systems which can be networked and a platform for developing customer-specific steer-by-wire solutions round off the diverse portfolio. With this portfolio, ThyssenKrupp intends to meet the more stringent emissions requirements as well as OEMs' and car drivers' increasing standards of safety and comfort while simultaneously giving consideration to cost pressure.

ECONOMIC LIGHTWEIGHT STEERING COLUMNS WITH CFRP COMPONENTS

The objective of the InCar plus CFRP lightweight steering column project is to validate different manufacturing processes using CFRP for small, medium and large-scale production with focus on weight reduction and economic manufacture. Processes suitable for automotive production are available in the form of pullwinding for the column jacket and the RTM process with tailored-fiber preforms for brackets. With these, a maximum weight reduction of up to 60 % is achieved for steering column components and up to 25 % for a complete steering column with comparable performance. The components can be used in modular form.

Design engineers, simulation experts, manufacturing and automation specialists plus material experts with long-term CFRP (Carbon Fiber Reinforced Plastic) experience from various areas within ThyssenKrupp are bundling their expertise in the InCarplus CFRP lightweight steering column project. The objective is to develop CFRP steering column components with maximum weight reduction as well as economic manufacturing processes for large-scale production. The starting point of development is a selected, standard steering column made of sheet metal. Two typical components found in similar form in all steering columns are selected from this: the geometrically complex bracket and the profile-like column jacket, ①. These components are representative of the stresses and geometric complexity found in many other automotive components.

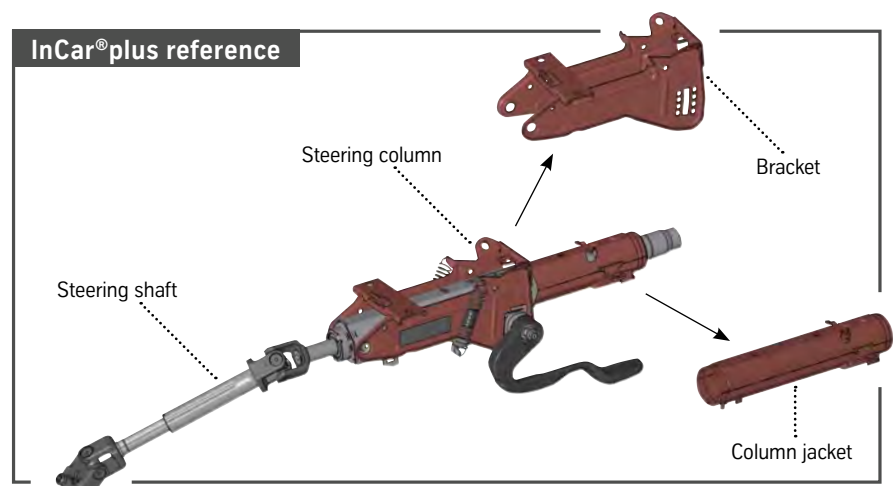
So far, steering columns have primarily been fitted with structural components made of metal; depending on design, requirements and target costs, either steel or aluminum and magnesium. To date, vehicle components consisting of CFRP are used primarily in extremely small-scale production, e.g.

motor sports and super sports cars approved for on-road use. One of the reasons for this is the continuing lack of economic manufacturing concepts for CFRP parts.

COLUMN JACKET

The column jacket on the reference steering column consists of longitudinally welded sheet metal and accommodates

the steering tubular column shaft with the steering wheel, ①. The steering tubular column shaft is used to transfer both steering torques and the forces which a driver entrains into the steering column, e.g. during “jacket straightening”. These forces and steering torques can be several hundred Newtons or Newton meters. In a crash, forces in the Kilonewton range actually occur due to airbag deployment and driver impact.



① Steering column with bracket and column jacket as well as steering shaft

The stress analysis in the component is the starting point for developing an optimal design along with economic manufacturing technology, ②. The stress analysis is first used to determine the stress status in the component and then derive the layer structure from this. A moderately complex stress status arises for the column jacket, as compressive, tensile and shear stresses are superimposed in the component due to the introduction of radial forces and bending torques at the interface to the steering wheel. There are also bearing pre-loads which have to be taken into consideration in the CFRP layer structure design.

At present, CFRP components for automobiles are primarily manufactured using preforms consisting of textiles and fabrics which have to be trimmed to the component contour. In the next process step, the preforms are inserted into a tool and injected with resin in the RTM (Resin Transfer Molding) process. The RTM process has been used in combination with braided preforms for the column jacket. However, difficult handling of the flexible preforms and the necessity of manufacturing cores to produce the hollow profile prevent economic production of profile-like components.

Pultrusion technology is an alternative to producing the column jacket using the RTM process. This technology is particularly suitable due to its high degree of automation, low offcut volumes and the avoidance of semi-finished products through the use of less expensive carbon fiber roving coils. Pultrusion, also called extrusion pulling when applied on isotropic materials, is an automated process for continuously manufacturing endless GFRP/CFRP profiles with a constant cross-section. The fiber rovings are unreel from coils and then pulled through a resin bath or injected with resin in an injection box directly upstream of the pultrusion tool. The resin is hardened in the pultrusion tool, which reveals the negative form of the desired profile. The finished profile is continuously drawn out of the tool and cut off according to the installation length. This technology is interesting for both small and large quantities, as the tool costs are comparatively low.

The pultrusion process makes the axially-oriented fibers available in extended form. A winding process applies the circumferentially-oriented fibers. If the

pultrusion and the winding process are combined, this is called pullwinding. All forces acting on the column jacket can be taken into consideration in this process.

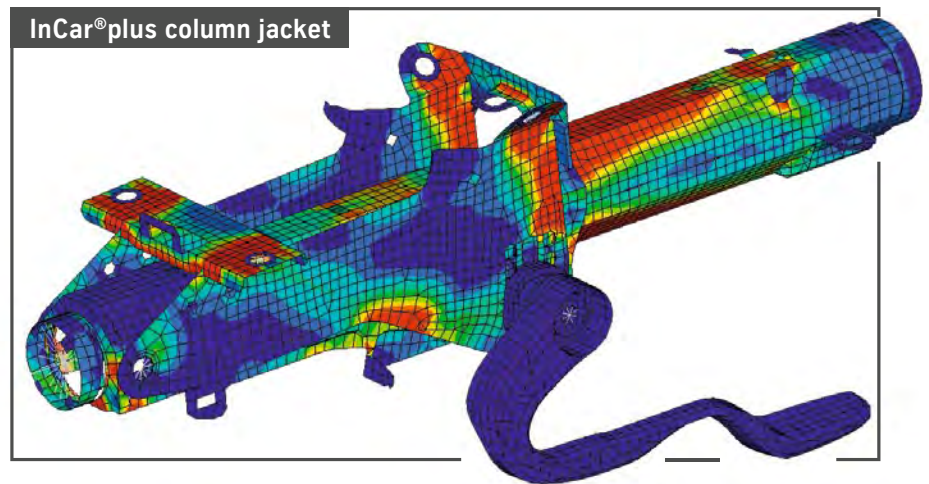
FEM analyses show that a CFRP pullwinding profile can replace a 2 mm steel profile with moderate geometric changes. The weight reduction from 600 g (reference component) to 260 g (CFRP column jacket) amounts to 56 % with acceptable lightweight costs. The mechanical properties of the pultruded components are very good, as the continuous and automated

drawing process ensures that the 0° layers' fibers are oriented precisely. The geometry of the pultruded components is so accurate that mechanical reworking is usually no longer necessary.

The pullwinding profile's stiffnesses are comparable with those of the steel profile, ③. Overload and crash tests confirm sufficiently high strengths.

CFRP BRACKET

Brackets join the steering column components to the vehicle and transfer the



② FEM analysis of the column jacket to define the layer structure



③ Verification of the required bending stiffnesses in technical tests

steering wheel forces acting on the bracket via the column jacket and to the vehicle. Steering column vertical adjustment is implemented using a slit and a pivot point in the bracket. The vertical and longitudinal adjustment mechanism is fixed in the steering column with a clamp system. Clamping forces, which are introduced into the bracket by the lever via the clamp bolt, overlay the forces and relevant stresses in the component. In all, these factors result in a complex stress status, ④.

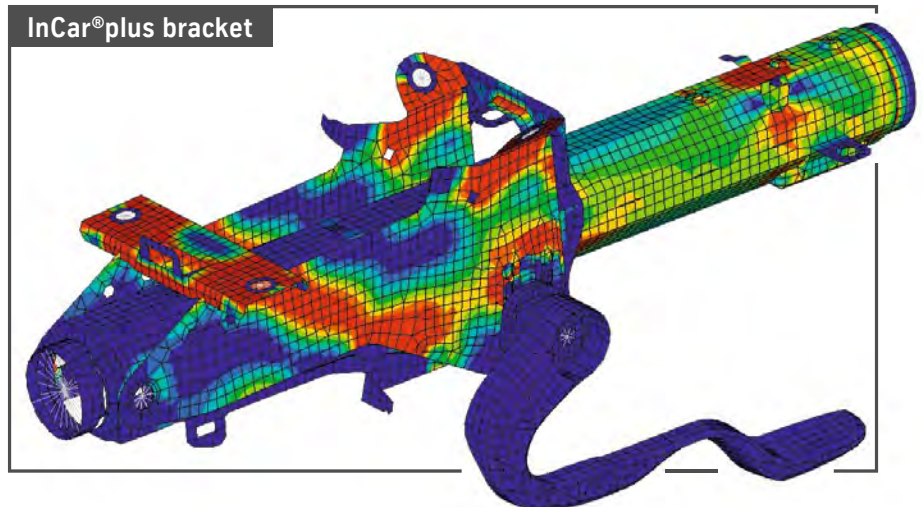
The main load paths in the bracket can be clearly seen, whereby a complex stress case prevails in the area of the lever due to the clamping forces and the bolt-on forces. The layer structures in the component are defined on the basis of the stress cases.

In combination with the RTM process, preforms consisting of fabrics and textiles have become established as the state of the art in manufacturing complex geometries. The following process steps arise:

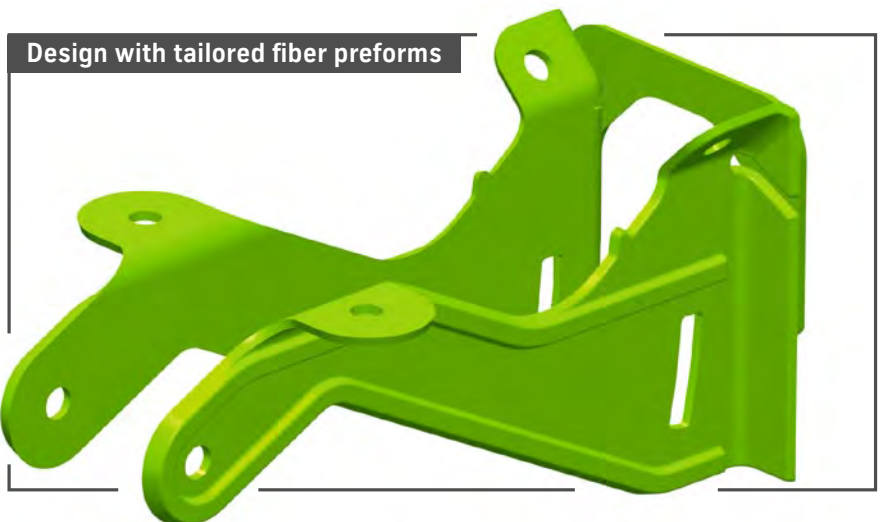
- : pre-cutting of fabrics/textiles
- : preform production through draping
- : preform trimming
- : RTM process
- : machining.

If the brackets are to be manufactured in one piece, a complex, multi-part tool is necessary. The investment costs are therefore higher, especially in the case of several tools for an increased yield. In the most favorable case, carbon fiber material exploitation is 43 % thanks to double trimming of the components with lasers and final trimming of the hardened components using a five-axis milling center. Construction phase 1 therefore reveals high investment costs for the manufacturing accessories, high material use and a long cycle time. However, it offers a weight reduction of 53 % in comparison with a conventional metal bracket.

These process steps are therefore being further developed as part of InCar plus. The reference steering column's bracket consists of several bent and punched sheets which are welded together. This concept is also applied for the CFRP bracket to obtain flat components and thus inexpensive tools. The bracket is subdivided into several separate subassemblies. This design enables reduced contour machining and minimized carbon fiber material loss. Several



④ FEM analysis of the bracket to define the layer structure



⑤ Load path-friendly and low offset layer structure thanks to tailored fiber preforms

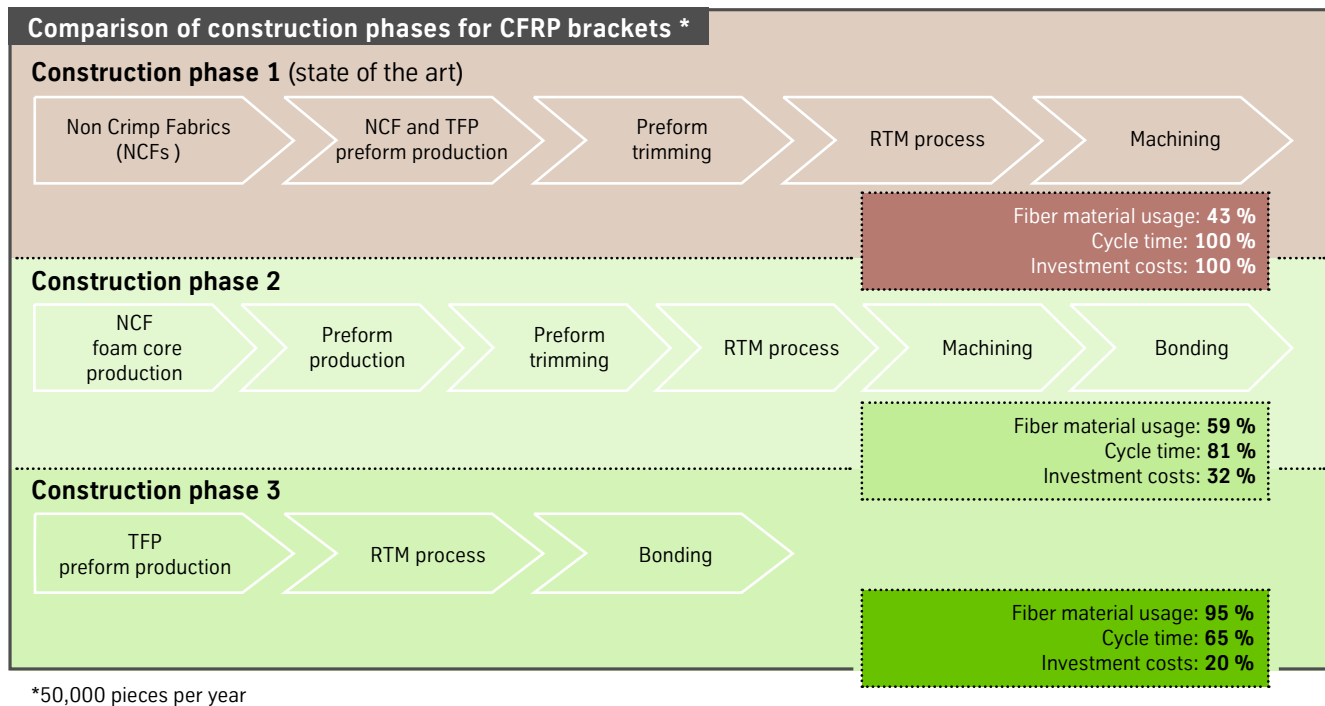
of these more simply designed CFRP subassemblies can also be manufactured simultaneously in a multi-cavity tool, thus reducing cycle times within the RTM process. To locally reinforce the side parts, a PU foam core is integrated into their center, thereby increasing structural stiffness. This 2nd construction phase achieves a weight reduction of 60 % (from 622 to 250 g).

The manufacturing process for this non-crimp fabric (NCF) variant encompasses the following six operations:

- : The individual textile layers are trimmed by a high-performance cutter which cuts out the semi-finished fiber products under consideration of the

calculated fiber orientation and a component offset. The foam core is manufactured in a multi-cavity foam tool using a dosing system. In this process, the prepared tool is closed and the pre-mixed and exactly dosed material is injected into the tool. The foam core can be removed after a short hardening time.

- : The preforms are manufactured in the so-called preform center. Here, the prepared layer packages (individual layers with binding powder) and the foam core are placed on a preform tool, where they are brought into shape and heated. The binding powder melts and holds the preform together.

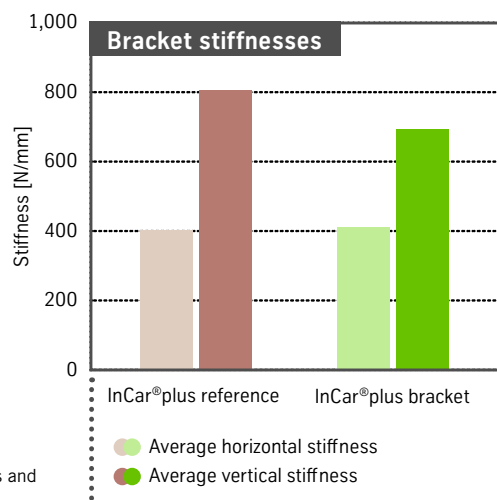


⑥ Improved process chain in comparison with the state of the art

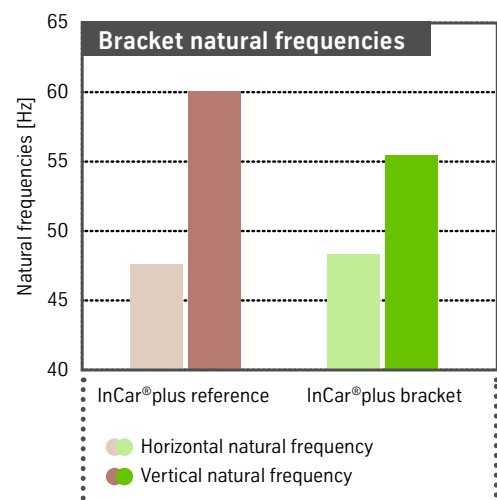
- : A laser then trims the preform to its final contour.
- : In the RTM process, the multi-cavity tool is loaded with the preforms and then infiltrated with the resin system. The components can be demolded after a hardening time of around 10 min.
- : In this construction state, machining is limited to the integration of drilled holes.
- : The final operation is bonding of the subassemblies.

Following the good results achieved in construction phase 2, the objective was to improve economy in a further construction phase. Thanks to detailed FE analyses of the bracket and simulations of various layer structures, only tailored fiber preforms can be used, ⑤. These TFP (Tailored Fiber Placement) preforms are produced directly from carbon fiber rovings in compliance with the force direction. The advantage in

comparison with preforms consisting of textile semi-finished products is the less expensive starting material, high material exploitation of approximately 95 %, the production of final contour preforms including passages and the reduction of operation steps, ⑥. In addition, multi-head embroidery machines can also manufacture several preforms simultaneously, thus significantly reducing the cycle times.



⑦ Horizontal and vertical stiffnesses and natural frequencies of the bracket



The preforms manufactured in this way can be inserted directly into the RTM tool without trimming and infiltrated with a resin system. After hardening, the components are removed, secured in a fixture and bonded together using two-component adhesive. The TFP variant offers a weight saving of 60 % with significantly lower costs than variant 2.

The bracket measurement results reveal a slight improvement in horizontal stiffness and natural frequency in comparison with the reference component, 7. Its vertical stiffness and natural frequency are already over dimensioned, with the result that the CFRP brackets meet the specified requirements.

Intensive development of the various processes and materials has also led to the creation of an expertise basis for optimum design for diverse application cases. Together with the optimal manufacturing process, this ensures that the most economic solution is always available.

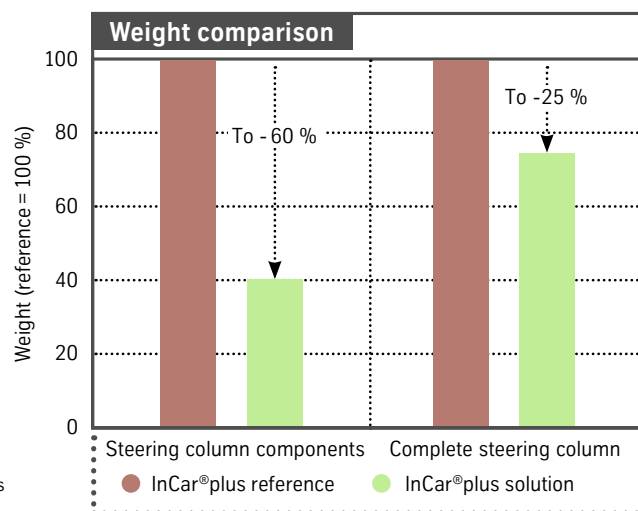
STEERING COLUMN

ThyssenKrupp uses the CFRP column jacket and bracket in lightweight steering columns in multi-material design and therefore reduces their weight by 25 %, 8. The CFRP components can be used in modular form depending on requirements and accepted costs. To validate component development and the manufacturing concepts, these CFRP steering columns were successfully subjected to endurance tests, crash tests on the drop tower, 9,

8 Significant weight reduction through InCarplus CFRP steering column

vehicle tests and acoustic tests in the laboratory and in the vehicle. The lack of any decrease in stiffness and natural frequency proves that the steering column characteristics remain constant even after stringent tests. ThyssenKrupp has therefore confirmed the suitability of CFRP even for complex, safety-critical lightweight structures in the area of the steering column.

The described manufacturing technologies and resulting components were successfully tested in various steering column projects and vehicle tests. In addition, the engineers paid great attention to interfaces to other materials such as metals, as phenomena such as thermal expansion and contact corrosion have to be taken into consideration here.

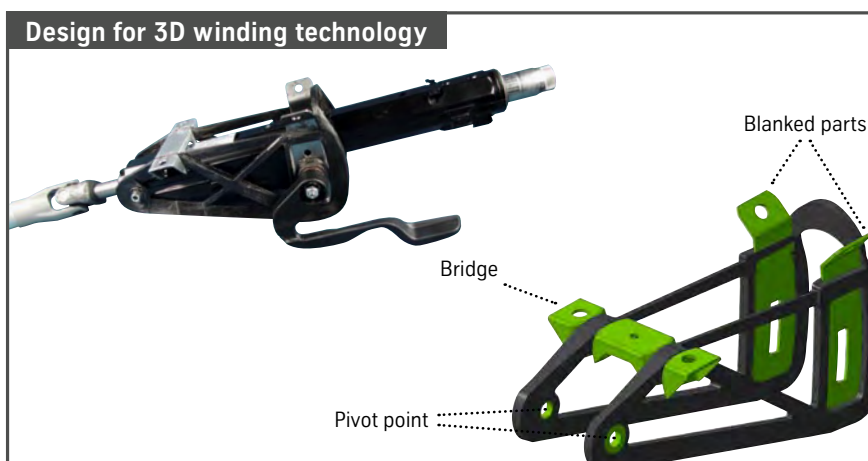


OUTLOOK

The TFP process for forming a spatial component is currently undergoing further development for brackets. Instead of the fibers being deposited flat on a base fabric, they are spatially wrapped by robots onto inserts in accordance with the direction of the force. In turn, the inserts are located on a tool which can be closed to inject resin between the fibers. Once the resin has hardened, the ready-to-install bracket is removed from the tool and does not have to be subsequently machined, 10. Rovings directly from bobbins have very little offcut and are highly economical. The manufacturing technologies presented are not only suitable for other components in steering systems but also for other vehicle application.



9 InCarplus solution in the drop tower crash test



10 Load path-friendly fiber deposition in three dimensions

HYBRID STEERING SHAFT: 35 % LESS WEIGHT

35 % less weight with lightweight design costs of less than € 5/kg: the new hybrid steering shaft, a lightweight tube-in-tube solution with aluminum yokes developed for optimum power flow, represents significant progress in comparison with the reference steering shaft. Its modular design also offers maximum flexibility. Depending on specific customer requirements, the universal joint's aluminum yokes can be replaced in whole or in part with steel yokes. The high-performance polymer which is used enables the sliding connection to temporarily withstand temperatures up to 200 °C.

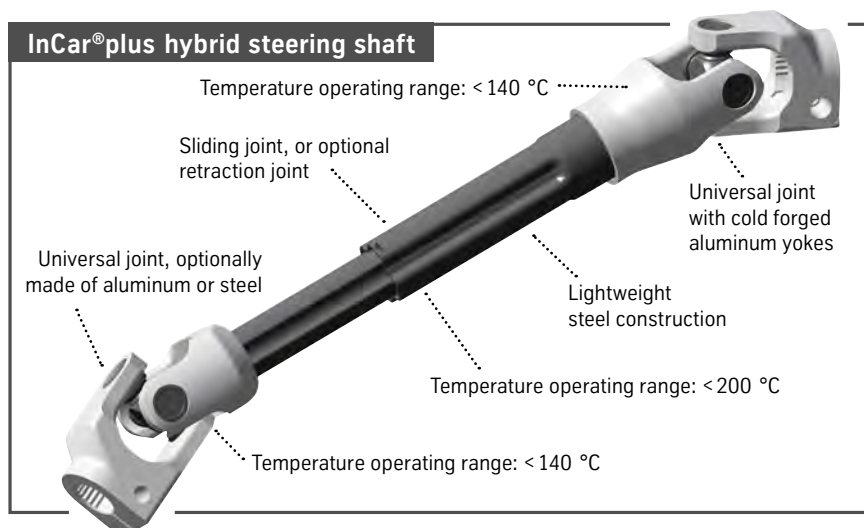
In optimizing familiar steering shaft concepts, the ThyssenKrupp developers set themselves a demanding goal: the result should be a significantly lighter steering shaft with at least the same performance and minimal lightweight design costs. A steering shaft which was taken from in-house production and

used as a reference reveals a shaft-in-tube sliding system and cold forged steel yokes. Cold forging enables complex geometries to be manufactured at low cost. The steel design withstands high operating temperatures. With a weight of up to 2.0 kg, however, the steering shaft still offers significant weight reduction

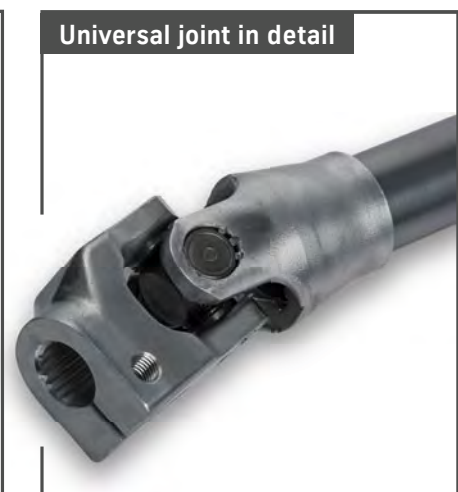
potential. This is where the new hybrid steering shaft comes into play, ❶.

MATERIAL SUBSTITUTION MAKES MANY THINGS LIGHTER

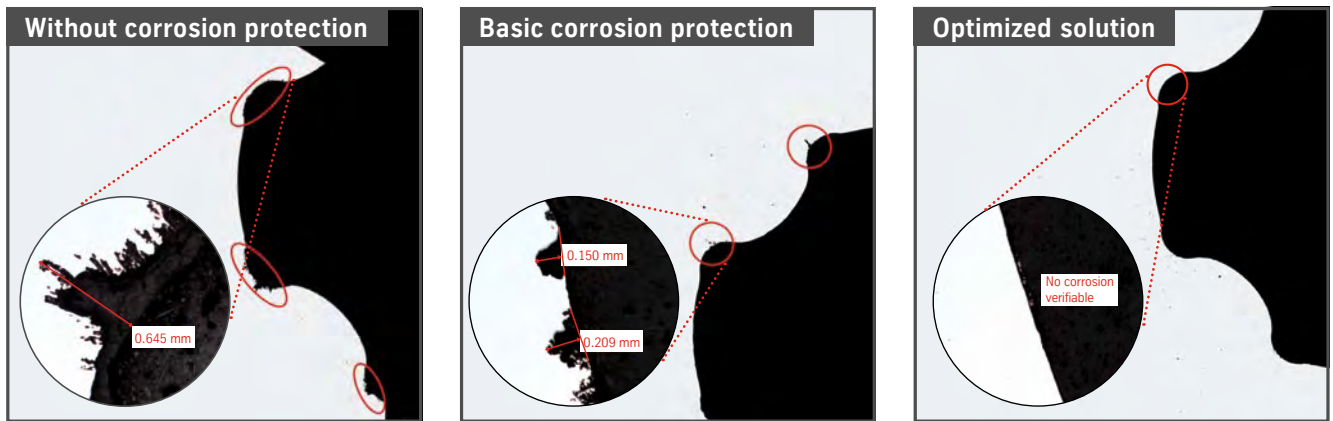
The sliding connection and yokes of a conventional steel steering shaft are



❶ Lightweight hybrid steering shaft



❷ Lightweight aluminum universal joint



③ Corrosion test micrographs

Material	Steel	Steel/aluminum hybrid solution	Aluminum
Weight	1.50 kg	0.98 kg	0.78 kg
Costs	Reference	10–15 % higher than the reference	10–20 % higher than the reference
Temperature range	Entire steering shaft: ≥ 200 °C	Tube section: up to 200 °C short-time Universal joint: up to 140 °C short-time up to 130 °C permanently	Entire steering shaft: up to 140 °C short-time up to 130 °C permanently

④ Comparison of the various steering shaft concepts and their characteristics

responsible for around 90 % of its weight. Consequently, these components form the focus of lightweight design activities. The engineers are pursuing two approaches: lightweight material in the universal joint, ②, and structural lightweight design in the sliding connection.

So far, the universal joint's steel yokes have above all been optimized for manufacturing in the cold forging process. Thanks to the relatively high modulus of elasticity of steel, a design with optimized stiffness has not thus far been necessary to the same extent. In contrast, substitution of the steel yokes with aluminum yokes necessitates optimization of the yoke geometry stiffness. In combination with a yoke design optimized in terms of power flow, however, this material substitution leads to very high lightweight potential expectations. For example, the aluminum material enables the realization of a universal joint which is significantly lighter than before and which meets the same static and dynamic strength requirements as the reference component. This applies similarly to package requirements and the rotational bending angle.

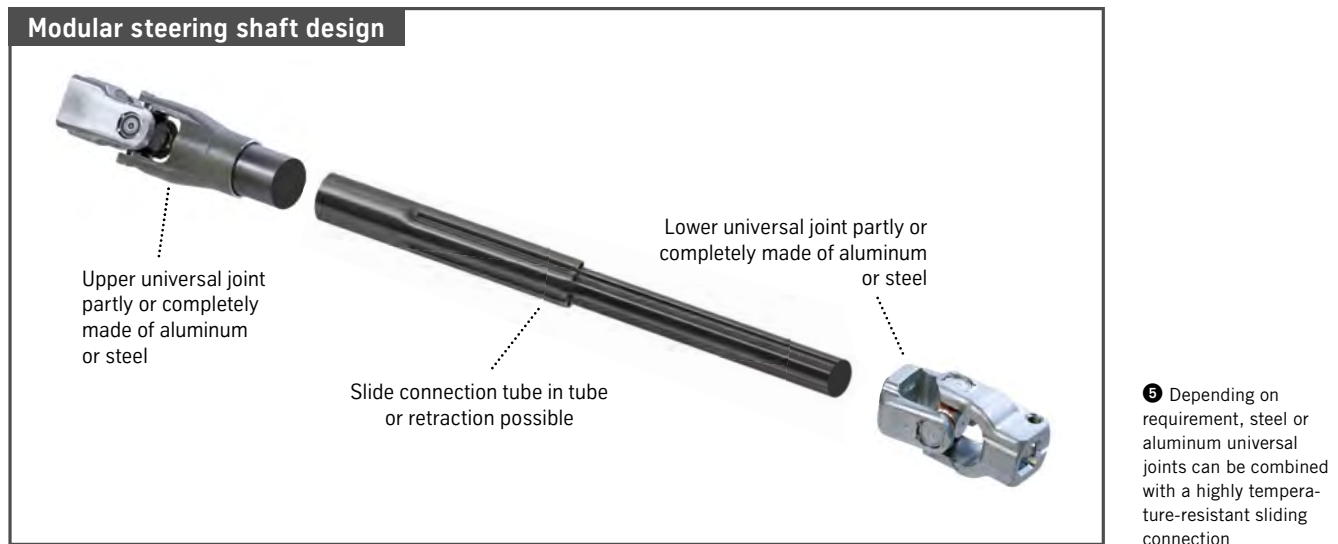
The sliding connection, previously a solid steel shaft with tube, is being replaced by a tube-in-tube solution. The use of a tube material with higher characteristic strength values simultaneously enables the wall thickness to be minimized. As a result, the weight is reduced while torsional stiffness is increased at the same time. In all, these measures lower the total weight of the reference steering shaft from 1.5 kg to just 0.98 kg. This equates to a weight saving of around 0.5 kg or 35 %.

MANUFACTURING AND CORROSION

The hybrid steering shaft assembly processes are based on ThyssenKrupp's many years of experience in manufacturing steel steering shafts. Existing and proven processes can therefore be implemented and economic steering shaft production ensured. The manufacturing process used for the aluminum yokes is cold forging, a process which ensures inexpensive production, particularly in high volumes. Without additional, subsequent machining of the initial geometry, it also enables high rotational bending angles and very small component

dimensions. The aluminum yoke and steel tube are joined using an assembly process similar to that of steel steering shafts. To rule out malfunctions, additional mechanical caulking redundantly secures the joint.

In the steering shaft, this hybrid design brings together two materials with different electrochemical potentials. To make matters more difficult, the steering shaft is located in whole or in part in the engine compartment and is therefore exposed to extensive dirt and saltwater entrainment plus temperature stress. This essentially leads to a risk of contact corrosion. The solution which has been tabled provides for a special protection concept which can completely prevent corrosion. ③ shows micrographs of various specimens after a long-term corrosion test. The specimen on the left shows a component without any protection and accordingly severe corrosion. The specimen in the center has basic protection which reduces the corrosion but does not essentially prevent it. The optimized solution is shown in the specimen on the right. No corrosive attack is detectable here.



INEXPENSIVE WEIGHT REDUCTION THROUGH MATERIAL MIX

Below the line, lightweight design costs of € 5/kg are incurred. The hybrid steering shaft therefore offers inexpensive lightweight design for high temperature requirements. Comparison with other steering shaft concepts confirms these positive characteristics, ④. While a conventional steel steering shaft is slightly less expensive, it is considerably heavier than the hybrid solution. Although a full aluminum steering shaft may be slightly lighter, however, its costs are higher, in part, than those of a hybrid steering shaft. One serious disadvantage of the full aluminum steering shaft is its limited thermal resilience.

WITHSTANDING HIGH TEMPERATURES

Depending on vehicle packaging concept, the steering shaft may be located very close to the exhaust manifold, with the result that surface temperatures of 200 °C are not uncommon. The hybrid steering shaft can be used at these temperatures. The full aluminum variant is unsuitable for these operating conditions. The steering shaft's sliding connection is located precisely in this highly stressed area, ⑤ (center.) Despite these high temperatures and the related change in material characteristics, however, the sliding connection has to remain fully functional. Thanks to a high temperature-capable

sliding sleeve and special grease, the hybrid steering shaft also guarantees this at peak temperatures of up to 200 °C.

If the sliding connection is intended to collapse at a defined crash force, it must also be possible to implement the required characteristic at these high temperatures. To achieve this, the InCar plus solution provides for a steel-on-steel retraction connection. In this solution, no plastic element which limits the temperature is located between the tubes. As a result, the sliding connection is actually able to temporarily withstand temperatures of more than 200 °C.

The universal joints' yokes are manufactured from aluminum. They offer the required performance up to a defined operating temperature of 130 °C. Temperatures of up to 140 °C are also tolerated in the short term.

MODULAR CONCEPT WITH DEVELOPMENT POTENTIAL

The hybrid steering shaft is a modular and flexible system and can be adapted to the conditions in various vehicles. If required due to the operating temperatures, the universal joints' aluminum yokes are completely or partially replaced with steel yokes, ⑤ (left and right). The interface to the steering gear and the steering column is individually adapted for each automotive manufacturer.

On use of a complete system from ThyssenKrupp consisting of a steering

column and steering shaft, efficient connection enables minimization of the vehicle manufacturer's assembly effort. A sliding connection or a retraction connection is the appropriate solution depending on the vehicle, assembly and crash concept.

A standard sliding connection is sufficient for operating temperatures up to 80 °C; the above mentioned high-temperature sliding connection has to be implemented up to 200 °C. This concept, which only offers two stages, significantly reduces variant diversity within a platform. The steering column length and phase angle adaptations are also variable.

The hybrid steering shaft is suitable for all vehicles with dynamic torques up to 50 Nm. Accordingly, a set of specifications encompassing the automotive manufacturers' most stringent current tests for applications in the non-column EPS sector exists for the static and dynamic hybrid steering shaft tests. The hybrid steering shaft meets all of these requirements.

To further increase its added value, ThyssenKrupp is planning modules which integrate further functions. For example, a damper system could additionally filter oscillations and vibrations in the steering train. Further components could be manufactured from aluminum for applications subject to lower temperature requirements, thus accessing additional lightweight design potential.

LIGHTWEIGHT, HOLLOW STEERING RACKS

Due to their hollow cross-section, the assembled sheet metal racks developed in the InCar plus project are 0.5 kg or 25 % lighter than machined steering racks and enable both constant and variable toothing. This offers an attractive lightweight solution for steering gears which can be used with a gear ratio that has been chosen for optimum steering characteristics and possibly a smaller electromechanical steering support motor. The manufacturing costs are approximately on a par with conventionally manufactured variable racks.

Racks are a central component of a steering gear. They transform the steering wheel's rotary motion into linear displacement which in turn acts on the wheels via the tie rods. Weighing several kilograms, racks contribute extensively to the overall weight of a steering gear, as a result of which they are targeted by lightweight design strategists. The main objectives for the InCar plus solution are its general manufacturing feasibility, low manufacturing costs and tolerances, high part durability, low acoustic profile in the vehicle and a system concept for volume production.

The prototypes are based on a four-part rack design, ❶, with a formed toothed segment as the core element. An end segment with a thread connecting the tie rod is welded onto one side of this. A ground tube for guiding the rack using plain bearings is attached to the other side followed by an end section with thread. The thread diameter is freely selectable. Integrating the thread directly at the end of the toothed segment and the tube is a conceivable alternative. However, the thread diameter then has to be adapted to the relevant component diameter. The tie rod threads must also be adapted if necessary.

A possible process chain for manufacturing this assembled sheet metal rack includes the following steps, ❷.

It starts with manufacturing a sheet metal blank from coil material and bend-

ing it to form a U-shaped profile. An open profile shape is created through shear cutting and die bending. The trimmed parts are determined throughout the entire sequence by means of FEM material flow simulations.

The second process step is coining the tooth. This is carried out with press forces of 800 to 1500 t depending on workpiece size. As the toothing dies are subject to very high stresses, they are mounted in a reinforcement. The toothing dies are manufactured using HSC milling; the form tolerances are a few micrometers.

The profile, including the toothing, is then formed into a closed body. This process is subdivided into several steps. Forming is again undertaken as bending in the die, whereby deformation of the toothing during closing is avoided through the cross-section form. The

toothing segments, end sections and tubes are then finally machined.

The fifth step is laser beam welding. A precise clamping facility ensures that the components are aligned precisely to one another, especially the tube axis to the toothing. As the toothed segment material has a high carbon content, inductive pre- and post-heating of the heat-affected zone is necessary. The actual welding process only takes around 2 s per seam. Cleaning all components prior to welding is important for good seam quality.

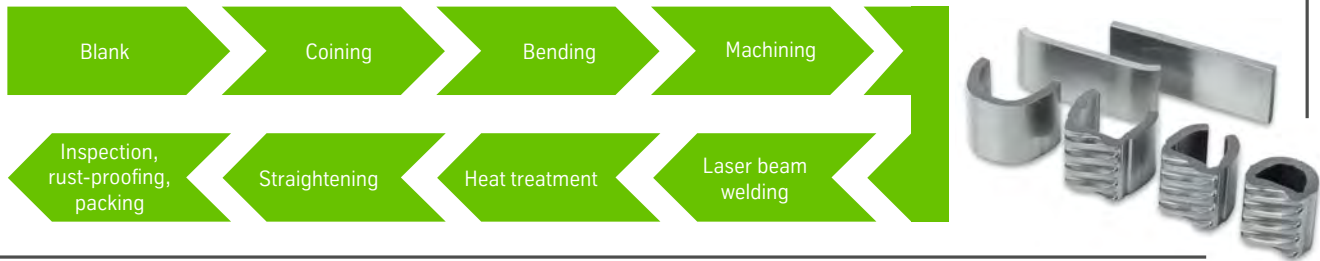
In the sixth step, the toothing is heat treated. To achieve higher wear resistance and component strength, the toothed segment is inductively hardened and annealed to values of 500 HV10. This can be undertaken using both the progressive method and with a full surface inductor.

InCar[®] plus solution



❶ Hollow, four-part steering rack

Steering rack process chain



2 Process chain for manufacturing the hollow steering rack

Finally, the racks are straightened after hardening to compensate welding and hardening distortion and to orient the toothing horizontally and vertically to the tube axis. In practice, these seven steps will be supplemented by further processes such as crack testing or preservation.

HIGH FORCES, LOW NOISES

The design of the prototype racks is very similar to the standard rack fitted in a subcompact car. This enables direct comparisons between both concepts. Variables of significance to steering behavior include push force and what is called yoke clearance.

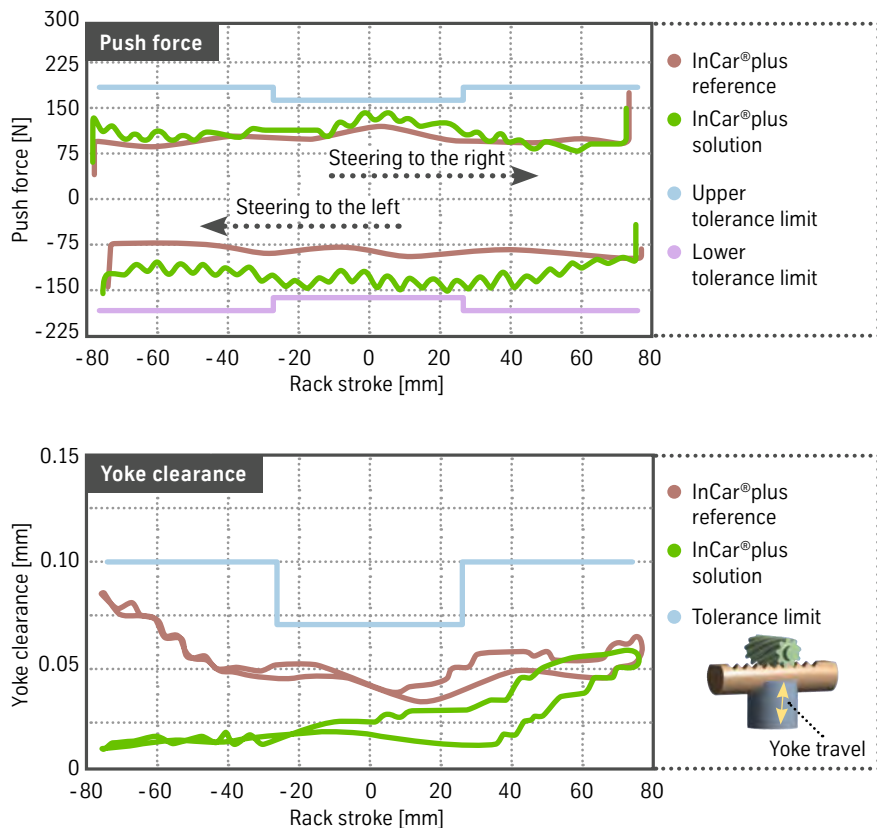
The push force is determined via the rack stroke in both directions. To do this, the rack is pushed through the steering gear. The sheet metal rack-type gear's force curve level corresponds to that of a standard gear, 3.

The yoke clearance characterizes the yoke travel over the rack stroke. The yoke presses the rack against the steering pinion and is able to compensate rack thickness fluctuations. If the rack becomes thinner, the yoke clearance increases, which may lead to acoustic anomalies. Measurements prove that the sheet metal and standard racks are comparable in terms of clearance. To test the gear unit's acoustic behavior, it is installed in a prototype steering system in a production vehicle. Acoustic assessment criteria include noise on driving over a torture track or on abrupt steering while stationary. These are assessed subjectively by test drivers. They attest to the fact that the sheet metal rack and the

standard rack reveal comparable acoustic behavior.

After verifying the general feasibility of hollow steering racks using the example of a subcompact car steering gear, further development will concentrate on hollow steering racks in rack EPS systems (Electric Power Steering) for larger vehicle classes. In these, the supporting

force will be applied using a threaded ball drive or a second toothing unit. ThyssenKrupp is anticipating weight and manufacturing cost advantages here – through the combination of vehicle-specific toothing on the driver side with a standardized threaded ball drive or a power steering toothing unit which is identical in various systems.



3 Comparison of rack push force (top) and yoke clearance (bottom)



ThyssenKrupp InCar[®]plus

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ThyssenKrupp

SUPERIMPOSING ACTUATOR: HIGH PERFORMANCE AT ATTRACTIVE COSTS

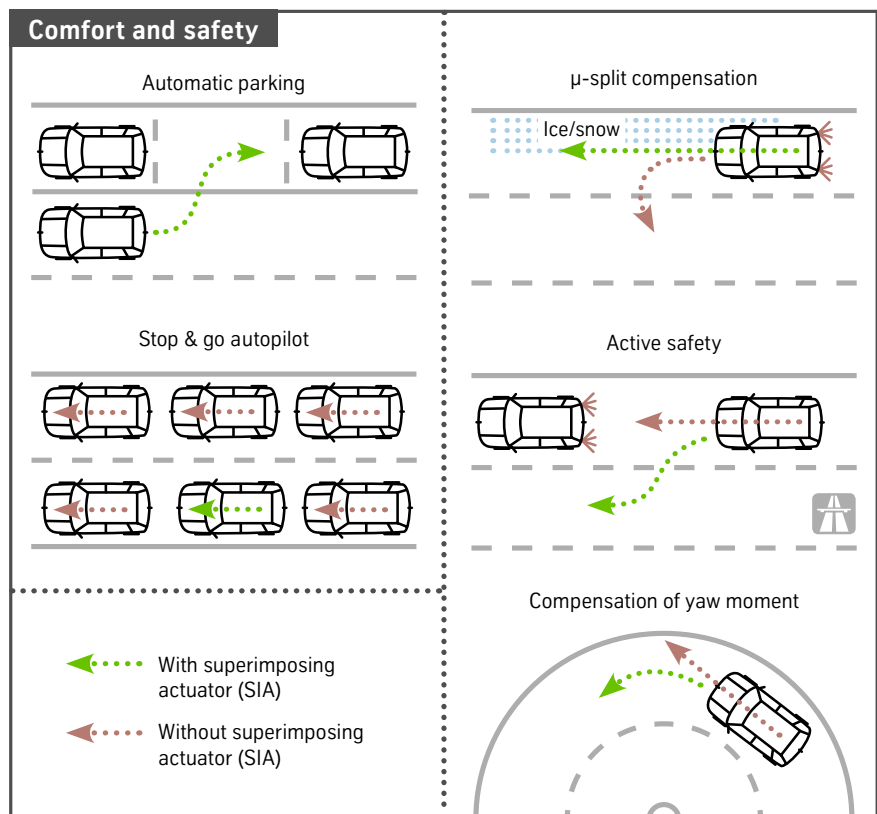
The superimposing actuator is an important part of the electromechanical steering. It offers a freely programmable steering ratio and therefore enables a variety of steering support functions. In technical terms, active steering intervention is based on an electric motor and a superposition gear, which as the core element of the superimposing actuator extensively influences its acoustic characteristics. Plastic gears offer adequately high performance for the overlay transmission at competitive costs. ThyssenKrupp has already demonstrated the performance of the complex mechatronic system independently of the motor.

A freely programmable steering ratio is a basic prerequisite for a variety of steering support functions for increasing driving safety and driving comfort:

- : increased comfort thanks to vastly smaller steering wheel angles during maneuvering or parking, ❶
- : greater agility through a direct steering ratio, e.g. at low speeds in urban traffic
- : better stability at high speeds on highways
- : contribution to increased safety through active steering intervention in critical situations (track stability in μ -split situations, cross-wind compensation or lane keeping), ❶
- : individual steering ratio characteristics, e.g. depending on the vehicle's driving dynamics modes.

QUIET PROGRESS

As vehicle manufacturers now expect mechatronic systems to offer increasingly better acoustic characteristics, the superimposing actuator, which is positioned in the interior between the steering column and steering shaft, also has



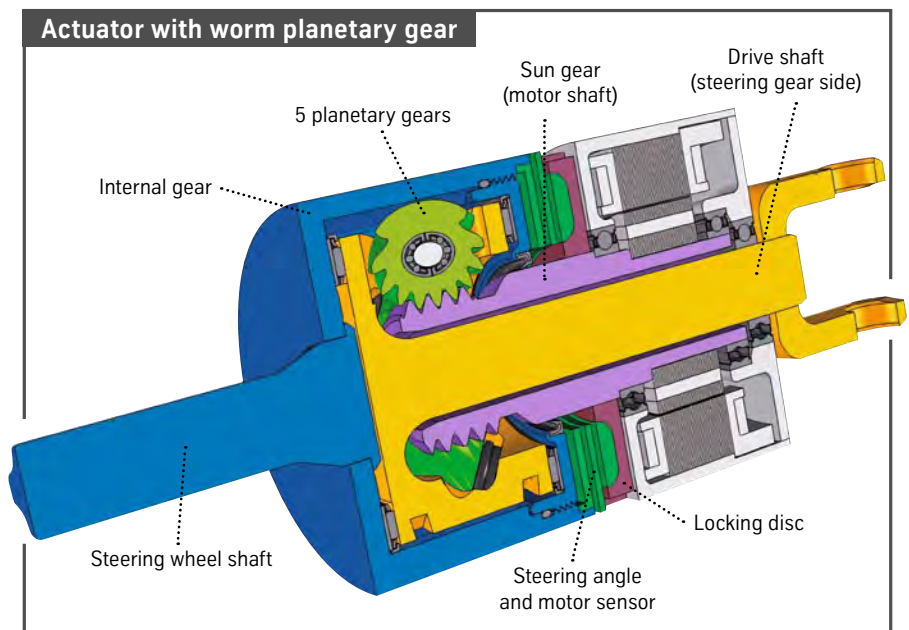
❶ Increased driving safety and comfort through integration of the InCarplus superimposing actuator into the steering system

to meet high acoustic requirements. A modular actuator design meets the functional and economic requirements best, as the individual modules such as the superposition gear, the electric motor and the safety brake can be developed, tested and optimized independently of each other. This shortens system development and enables the acoustic characteristics to be analyzed and improved more specifically.

As the core element of the actuator, the superposition gear extensively influences its performance due to the complex tooth intermesh movement sequences. ThyssenKrupp initially investigates and evaluates various gear concepts with symmetrical and asymmetrical load path. A planetary gear set with symmetrical power flow, in which the sun gear (motor shaft) acts as a worm, ideally meets the specified requirements in the given package, **2**.

The planetary gear set's advantages are its compact design and symmetrical load path, as a result of which only minimal transmission vibrations are introduced into the steering train. Distribution of the steering forces to several planetary gears reduces the respective stresses so that planetary gears manufactured from plastic can be ideally implemented, **3** and **4**.

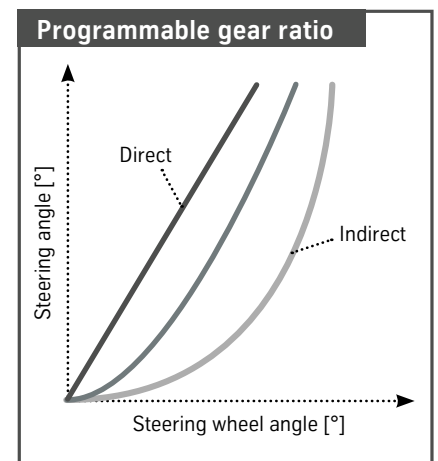
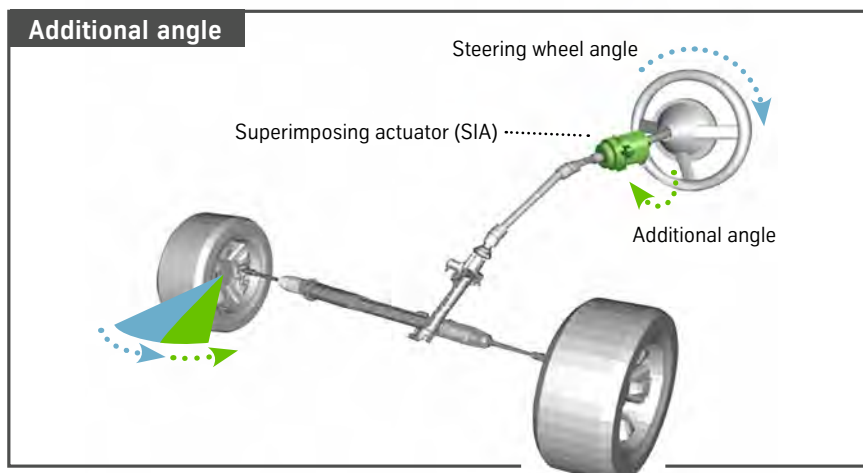
These planetary gears roll very quietly in the internal gear or on the worm (sun gear). The lower stiffness of plastic in comparison with steel means that the tolerance require-



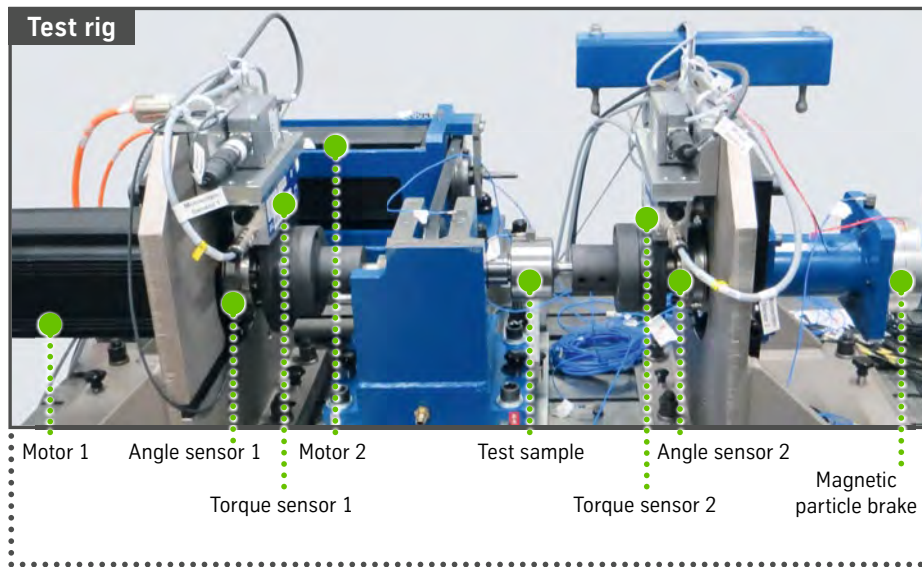
2 Sectional view of the actuator



3 Superimposing actuator transmission with plastic gears



4 With its freely programmable steering ratio, the superimposing actuator enables a variable steering wheel angle to steering angle ratio



5 Superimposing actuator on the test rig for acoustic and wear tests

ments of the toothing in the internal gear, on the worm and the planetary gears can be significantly reduced. This improves economy, as do the lower manufacturing costs for the plastic gears in comparison with steel gears. Another advantage is the high gear ratio in the first gear stage (worm – planetary gears). This limits the number of high-speed actuator components to the motor shaft with worm and the motor bearings, leading to corresponding acoustic advantages.

GEAR DESIGN VALIDATED BOTH VIRTUALLY AND EXPERIMENTALLY

ThyssenKrupp validated the design of the superposition gear with FEM simulations and prototype tests on the test rig. To do this, the gear prototype is clamped between the steering wheel and steering gear shaft, and is subjected to braking and drive torques at the shafts. The angular velocities and torques are recorded at the shafts. The modular design enables the gear prototypes to be driven using a separate motor (motor 2), 5. This drives the worm with a V-belt.

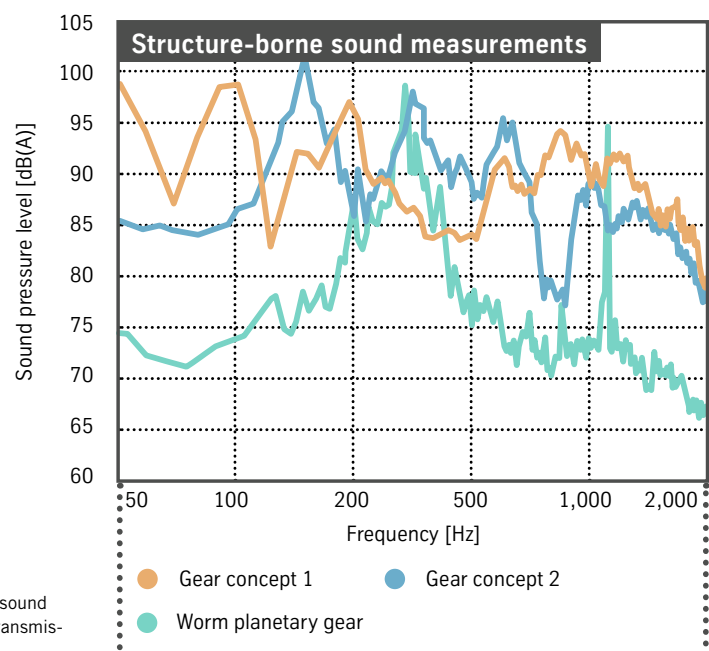
The gear prototypes meet all of the acoustic, lifetime and wear requirements specified by several European automotive manufacturers. The gears for all tests are manufactured from PEEK in a near-production injection

molding process and impress with their unreserved suitability for volume production.

Acoustic measurements clearly show that the planetary worm gear set's structure-borne sound, measured directly at the internal gear, is usually significantly lower than that of the reference gear concepts over the entire frequency range up to 2000 Hz, 6. Plastic gears can easily transmit the manual steering torques of

<5 Nm that are common during vehicle operation.

However, validation also encompasses an analysis of misuse scenarios up to and including component failure. 7 shows the hysteresis widths and the accompanying evaluation at a maximum required torque of 250 Nm at rated load and at the zero axis crossing. The plastic gears successfully withstand this stress even when significantly more load cycles



6 Structure-borne sound measurements on transmission prototypes

are implemented. They only reach their stress limit when overloaded with 130 % of the maximum required fracture load, thus confirming the gear set's high reliability.

ThyssenKrupp determines the friction and wear values of the tooth surfaces in a graduated process. Different combinations of plastics and surface coatings were initially investigated in model tests, and those with the best friction and wear values were determined. The best of these combinations were set up as gear prototypes and studied in endurance tests.

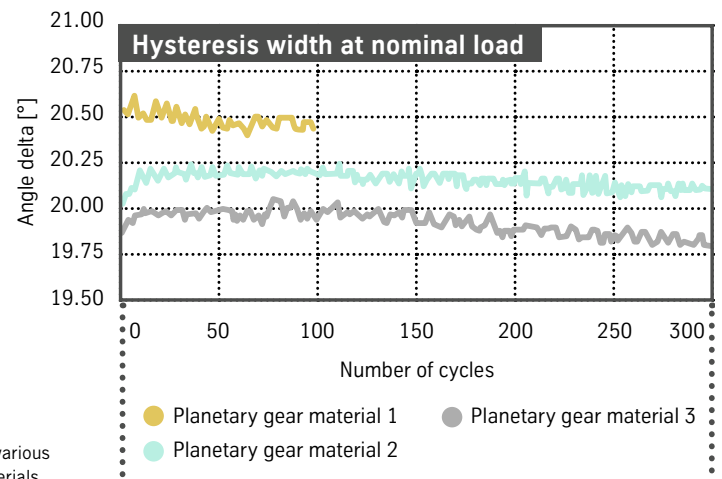
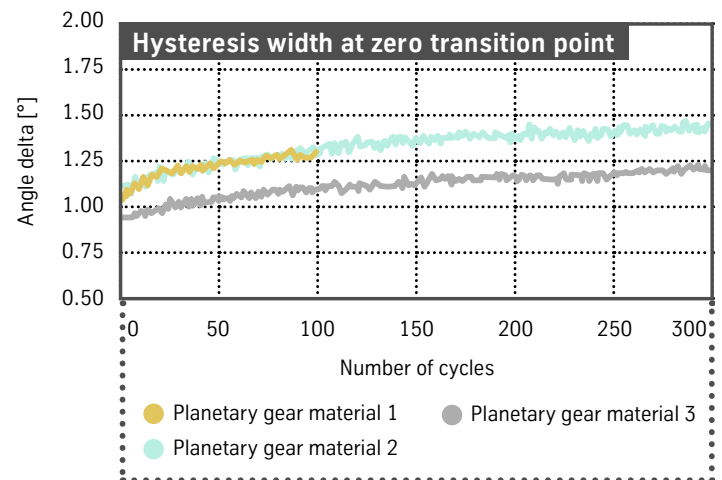
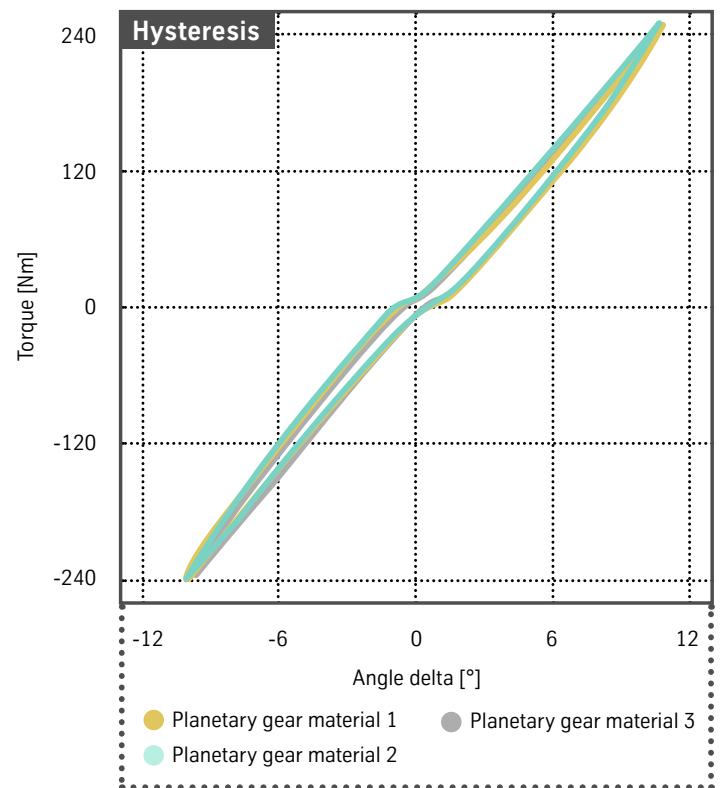
FOCUS ON COSTS AND CUSTOMERS

The use of plastic gears in the gear set offers certain cost advantages. First, the manufacturing costs by using the injection molding method are very low. Plastic gears are also less sensitive to tolerances during assembly than metal gears. Indeed, the planetary worm gear set is relatively easy to assemble. After assembling the axle and bearing in the planetary gear, this module is inserted into the planet carrier. Finally, the planet carrier is inserted into the internal gear and the pre-load on the planet carrier is adjusted using the cover. An additional cost-cutting measure is the fact that the gear set is assembled using a number of standard parts and mass-produced parts available on the market, such as spacer discs and planetary gear axles.

The overall superimposing actuator is constructed so that, in acoustic terms, the electric motor is positioned away from the driver on the steering gear side. The possibility of integrating an optional high-resolution steering angle sensor in addition to the motor position sensor is also provided. Together with the angle sensor signals, brake and electric motor, the superimposing actuator can be operated using a standard column EPS control unit.

The requirements specified for the overall superimposing actuator concept and the planetary worm gear set were met in the simulation and on the test rig. The next step is to construct a near-production actuator to be tested in an R&D vehicle. Cooperation with an automotive manufacturer is envisaged so that specific vehicle requirements can be integrated into the further development of the superimposing actuator.

7 Comparison of various planetary gear materials



COLUMN EPS FOR COMPACT AND MID-SIZE VEHICLES

In the InCar plus project, a column EPS (Electrical Power Steering) system has been developed for use in upper compact class and lower mid-size vehicles. It is available in two sizes for rack forces of 9 kN and 11 kN. Both steering feel and NVH have been considerably improved compared to current mass-produced column EPS systems. The column EPS system, which is located in the vehicle interior, allows significant cost savings to be achieved compared to rack EPS and pinion EPS systems, which are both installed in the engine compartment. It also requires less space in the powertrain and subframe area than these EPS systems. Column EPS is therefore a serious technical and cost-competitive alternative to the rack EPS and pinion EPS systems which currently dominate this vehicle segment.

Ever since the technology changeover from hydraulic to electromechanical power steering systems, most upper compact class and lower mid-size vehicles have been equipped with pinion EPS or rack EPS systems. So far, conventional column EPS systems have been unable to meet the steering feel and NVH requirements for premium vehicles

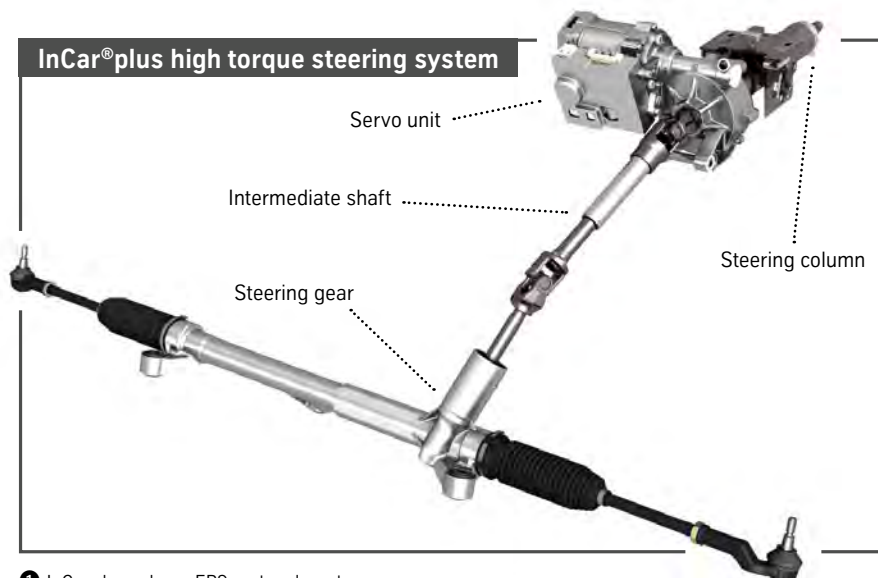
with the rack forces and steering performance required there. The steering feel of column EPS is impaired mainly by high servo unit friction and intermediate shaft compliance. Therefore, this type is currently more common in small cars and lighter compact vehicles.

With InCar plus, two new column EPS sizes with higher assist torques and rack

force capability have been developed, ❶: high torque with an output torque of 90 Nm and ultra high torque with 110 Nm. Depending on the ratio of the mechanical steering gear, the rack force that can be generated without compromising steering feel is 9 kN and 11 kN respectively. Both sizes use proven modules from ThyssenKrupp's EPS product range, which have been adapted to the increased output power. Other components have been developed from scratch or have been extensively modified. As an experienced system supplier, ThyssenKrupp has expertise in developing and validating all related hardware and software components.

SELF-ADJUSTING SERVO UNIT

In addition to rack load capability and output performance, the steering feel and noise behavior of the column EPS system must be as close as possible to that of rack EPS or pinion EPS for it to be acceptable for use in higher vehicle classes. ThyssenKrupp's advanced steering column torque controller is the basis for superior steering feel. Steering feel optimization was therefore focused on low servo unit friction, ❷, and interme-



❶ InCar plus column EPS system layout

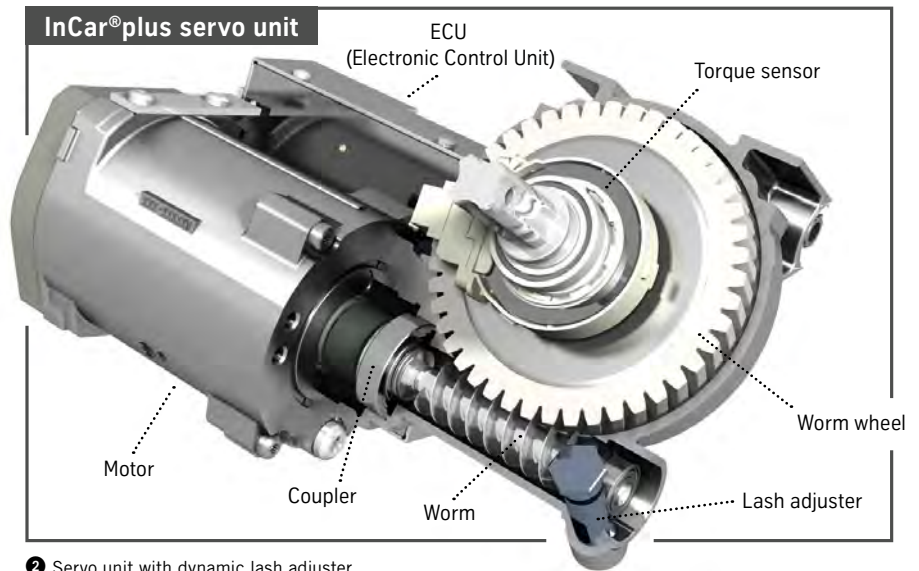
mediate shaft compliance. Friction and compliance compromise road feedback and lead to a generally synthetic and nervous steering feel. Through extensive, detailed work on the key mechanical components, servo unit friction and intermediate shaft compliance have been significantly reduced.

In the servo unit, the worm gear transmits the assist torque from the motor through the worm and worm wheel to the output shaft, ②. If a certain level of lash in the worm gear is exceeded, the result is rattle and reversal knock noise. At the same time, the compensation of gear tolerances and the different thermal expansion of the components mean that a certain minimum level of lash has to be maintained. Below this level, friction and torque fluctuation will increase exponentially.

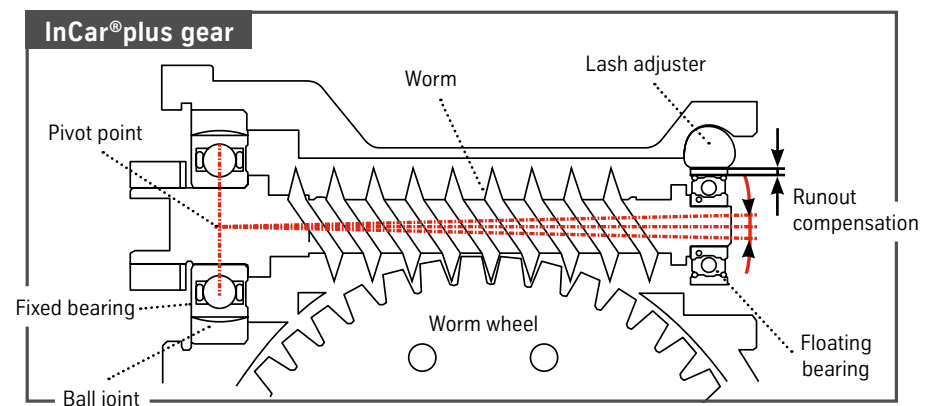
In order to prevent knock and rattle throughout the entire service life of the vehicle, a dynamic lash adjuster is required to compensate for component and assembly tolerances and wear. In smaller systems, this is commonly a simple preloaded spring, which presses the worm against the worm wheel to maintain lash-free gear meshing. The spring preload has to be configured in such a way that the worm does not lift off from the worm gear even at high loads. Beyond a certain system size, friction will be unacceptable in this simple system.

In the new dynamic lash compensation system, an automatic adjuster compensates for tolerances, wear, and thermal expansion, ④. Lash adjustment is performed only in load-free phases, thus allowing the necessary preload to be minimized. The adjuster, which is preloaded with only a very low spring force, presses the worm against the worm wheel to keep the gear mesh lash-free, ⑤.

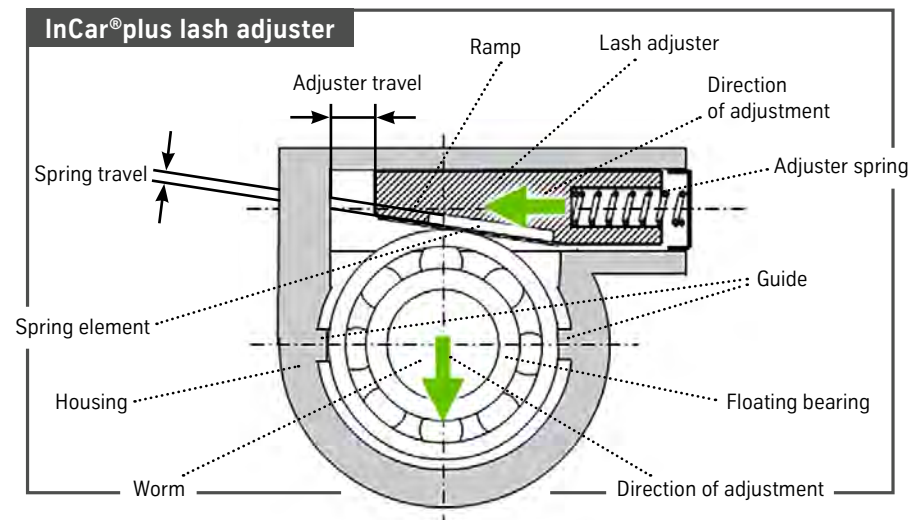
The adjuster is self-locking and does not slide back under load, which means that it is not necessary to preload it with the full design load. This significantly reduces servo unit friction. A secondary spring element with an end stop ensures a well-defined minimum lash. In this way, gear mesh tolerances and deviations of the centerline distance caused by the different thermal expansion of the components are compensated for, thus minimizing the torque fluctuations of the servo unit.



② Servo unit with dynamic lash adjuster



③ Lash-free gear meshing with dynamic lash adjuster



④ The lash adjuster is self-locking and does not move back under load

LOW-COMPLIANCE INTERMEDIATE SHAFT

The development of the new steering shaft was focused on the slider connection. The aim was to achieve dynamic length compensation while keeping the breakaway force under load as low as possible. A high breakaway force would lead to unacceptable knocking noise. The technical solutions currently available on the market do not meet these requirements at an assist torque of 110 Nm or over the vehicle's entire service life.

The new sliding connection consists of an outer tube with trapezoidal teeth with a large module and an inner tube with teeth that are coated with a tribologically optimized polymer. Elaborate fine tuning of the teeth geometries and the tribological system of coating and grease succeeded in significantly reducing compliance and breakaway force under load. New high-precision universal joints reduce rolling friction by 25 % together with increased stiffness.

PROVEN HIGH-PERFORMANCE ELECTRIC AND ELECTRONIC COMPONENTS

The three-phase permanent magnet synchronous motor of the servo unit is a proven module from the ThyssenKrupp EPS family. With 760 W and 5.8 Nm, the maximum motor output torque and power are in the range that is common for rack EPS. To prevent the motor from locking due to a short circuit and subsequent electromagnetic braking, different provisions have been implemented for reliable electric separation of the phases.

For example, the stator lamination in the winding area is encased in a plastic material. The winding geometry and fill ratio are designed to ensure that the different phase windings do not come into contact with each other. To avoid mechanical lock-up due to particles of broken magnets or other debris in the air gap, the rotor magnets are completely encased.

In order to minimize cogging and ripple, the rotor is step skewed and the slot/pole ratio is 3:2. The phase currents are space vector controlled with a current limitation in the ISO torque range and field weakening in the ISO power range. The pulse-width modulation frequency is above the relevant audibility limit. The stiffness-optimized stator, the elevated natural frequency and a reduction in vibration amplitudes minimize structure-borne noise emission in the operating range.

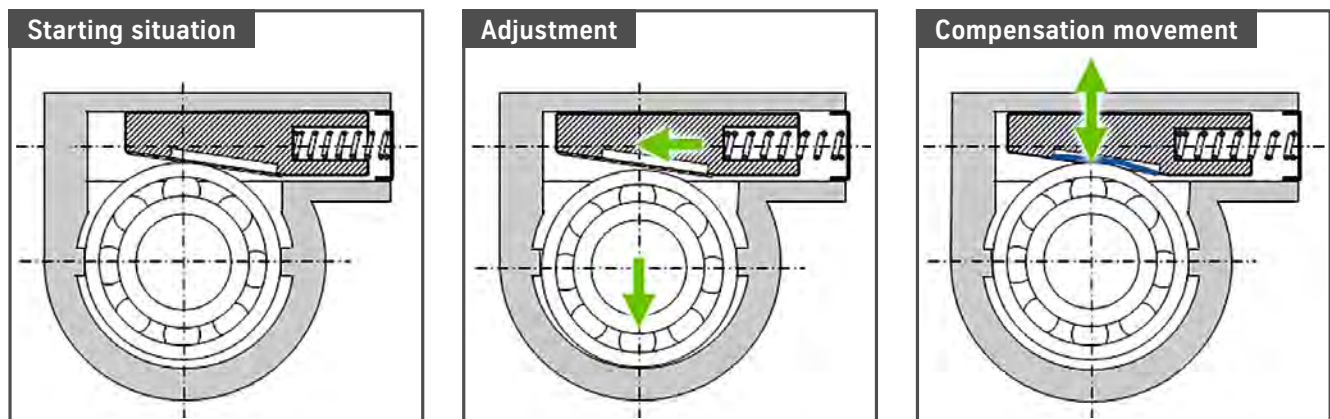
The control units have been developed entirely in-house and are part of the latest generation of the modular ECU family. In addition to the redesign of the power module, the control electronics have also been reduced in size and have been made more robust, ⑤. All development work was carried out in accordance with IEC 61508 and ISO 26262, and the entire system is fully ASIL D compliant.

The motor phases are controlled by six very low-impedance MOSFETs with a low power loss. At high currents, this is a prerequisite for high efficiency and thermal stability. For optimum cooling, the MOSFETs are directly bonded to the IMS board with its excellent heat dissipation. In the event of a short circuit, all motor phases can be disabled by three

additional MOSFETs. They replace the mechanical phase or star point relays and therefore significantly increase the robustness and reliability of the system. A detection circuit detects and prevents the avalanche effect which can occur when the MOSFETs are switched on and off, thus leading to phase relay short circuits. A current-compensated choke coil and two capacitors ensure good electromagnetic compatibility.

The dual-core main microprocessor is operated in lock step mode and complies with the ASIL D safety standards in connection with further software measures. It is operated with a 180 MHz clock frequency. The flash memory has a capacity of 1 MB. Safety-relevant functions are monitored by a robust watchdog processor, which disables the power unit via the Gate Driver Unit (GDU) in the event of malfunction. The GDU also performs under-voltage detection and acts as a gate and drain source monitor. Further diagnostic functions in the control unit are used to monitor internal voltages, temperatures and currents. The emulated flash EPROM reduces the number of components and complexity. A power ASIC developed by ThyssenKrupp is used for the power supply.

Communication with the vehicle is performed via a CAN interface and by FlexRay on customer request. The torque sensor communicates through a dual-channel SENT interface with current supply monitoring, which ensures that malfunctions are reliably detected. The rotor position sensor is connected via a UART interface. The system is powered up without delay when the ignition is switched on.



⑤ Functional diagram of the automatic lash adjuster

ROBUST AND PRECISE SENSOR SYSTEM

The ThyssenKrupp torque sensor, which measures the input torque, is compact and has proven itself in millions of EPS systems. With its magnetic measuring principle, it is resistant to contamination. A multi-pole magnet ring on the input shaft generates a magnetic field which is guided through the magnetic flux sensor in the housing by the magnetic flux collector on the output shaft. The input and output shaft are connected by a torsion bar. When a torque is imposed on the input shaft, both parts of the sensor are twisted against each other. The magnetic flux, which changes according to the twist angle and torque, is measured and the signal is processed. The signal transfer system from the rotating shaft to the stationary housing is purely non-contacting and has no collector rings or clock spring cables. The sensor is therefore free of wear and is aging resistant.

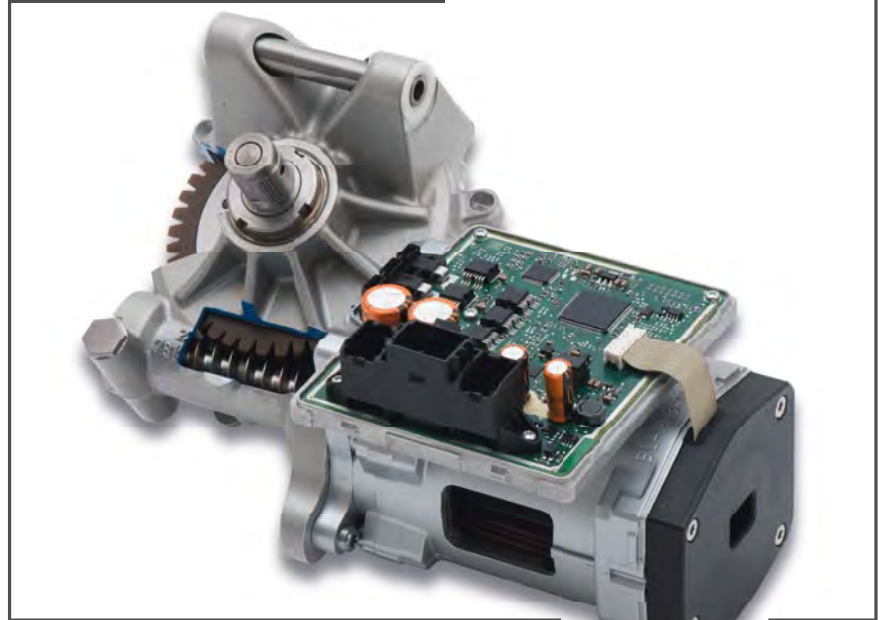
A magnet on the rear end of the motor shaft serves as a rotor position encoder. The magnetic field rotates with the shaft and is captured by magnetic flux sensors with a combination of various measuring principles. This enables very precise detection of the rotor position and motor control. This sensor and magnet arrangement is very robust towards axial and radial position tolerances and external magnetic fields. As a result, excellent NVH properties and low torque fluctuations can be achieved over the entire load and speed range.

The absolute steering angle is derived from internal signals such as the motor position with a plausibility check and correction through comparison and alignment with complimentary external signals such as the wheel speeds, etc. The rotor position sensor provides a very accurate angle signal, which is further refined due to the high ratio between the motor and steering column. Therefore, there is no need for a separate steering angle sensor to determine the absolute steering angle, thus resulting in cost, robustness, and package advantages.

AUTOSAR COMPATIBLE SOFTWARE

ThyssenKrupp was one of the first suppliers of electromechanical power steering systems to implement full AUTOSAR 3.1 compatible software in mass produc-

InCar[®]plus electronic control unit



6 Column EPS servo unit with control electronics

tion projects. AUTOSAR software modules developed by external suppliers are integrated with internal software modules such as motor control and application software. This allows shorter development times together with improved software quality. In-house AUTOSAR 4.0 base software has been developed together with a tool chain to implement customer-specific software quickly and flexibly. This enables customer or third-party software modules to be implemented quickly and safely.

All ThyssenKrupp column EPS systems use the patented steering column torque controller, which has already proven its superior performance in rack EPS systems. It is currently the benchmark with its clear road feedback and excellent tunability.

The system includes basic functions such as speed-dependent assist, active return, active damping, inertia compensation and an adaptive end lock. This makes it possible to flash different rack travels for different wheel sizes with the same mechanical steering gear via end-of-line programming.

Adaptive friction detection and compensation ensure the stability of the model-based steering feel over the entire service life of the vehicle. Interfaces for detecting understeer and oversteer support vehicle dynamics control systems

and functional ESP extensions. Parking systems and lane keeping systems obtain their signals from the rack position control system. Comfort functions such as personalization, pull/drift compensation and a lane-keeping assistant are also available. These and other modules can be configured and implemented according to customer-specific requirements.

The newly developed column EPS system for the rack force range from 9 to 11 kN is a genuine technical and cost-competitive alternative to rack EPS and pinion EPS systems for upper compact class and lower mid-size class vehicles. The optimization of its key mechanical components ensures that steering feel and acoustics are significantly better than before. It also offers package and cost advantages. ThyssenKrupp's holistic approach helps customers to exploit the full potential of column EPS for their specific application.

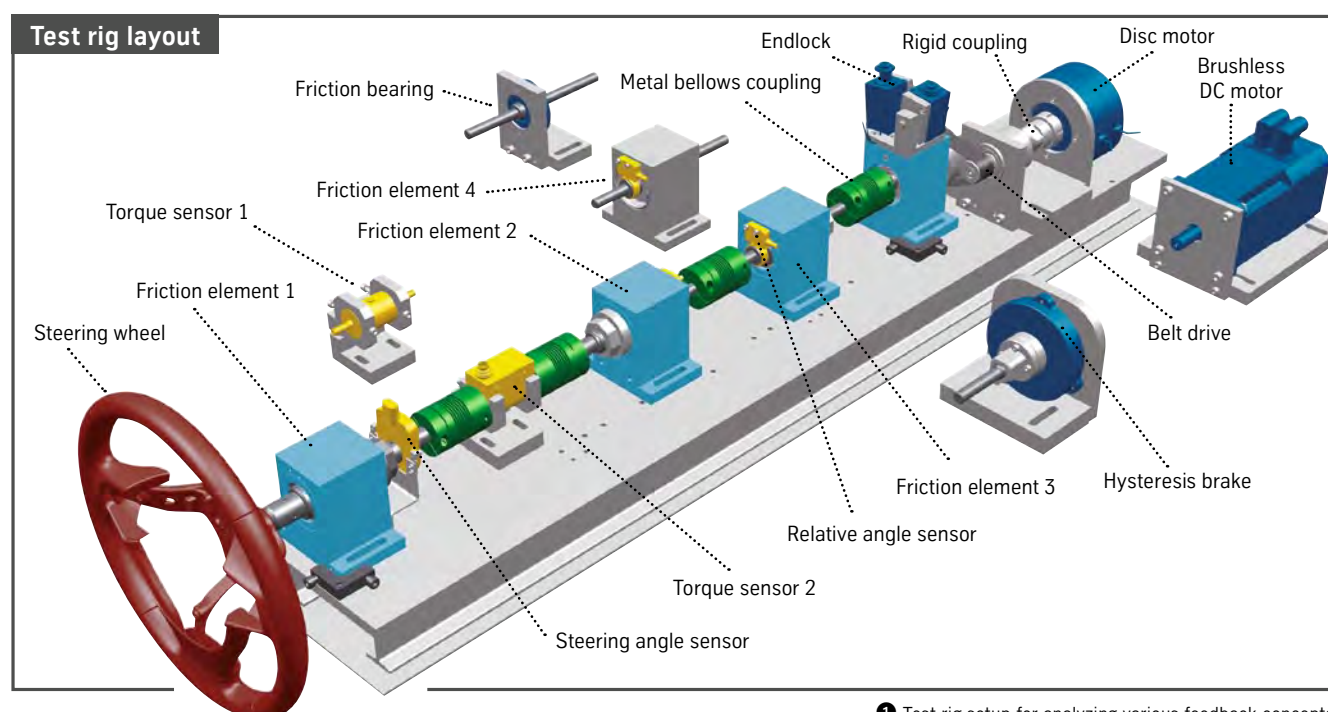
DEVELOPMENT PLATFORM FOR FUTURE STEER-BY-WIRE SYSTEMS

One of the biggest challenges in developing a steer-by-wire system is to simulate an authentic steering feel. In addition to a test object, ThyssenKrupp therefore also uses a test rig to analyze the feedback actuator system and its

components in detail, **1**. The integrated sensor system offers very high accuracy and resolution to enable even the smallest torque and angle changes to be detected. The torque sensor is not based on a torsion bar, as is otherwise usual.

Instead, a process involving differential magnetic field measurement in a rigid overall system is used to measure torque.

All of the influences of individual components and their interaction can be rep-



1 Test rig setup for analyzing various feedback concepts

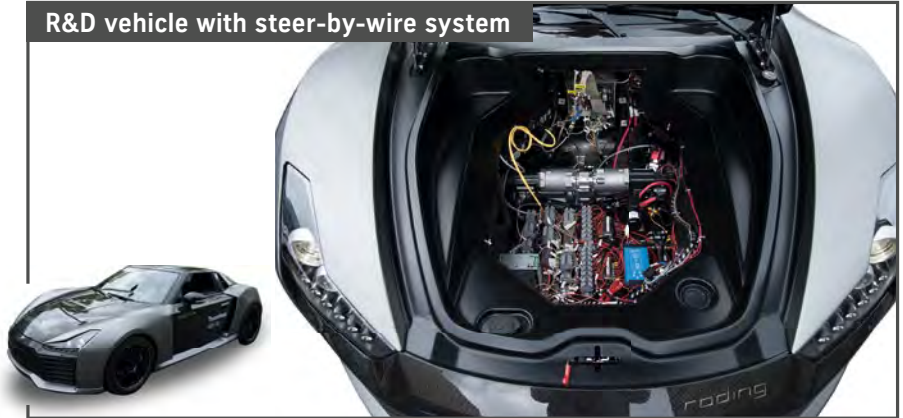
resented and analyzed on the test rig. The individual components can be variably combined and exchanged. The following components and concepts can be objectively and subjectively compared under identical boundary conditions:

- : friction in various positions
- : stiffnesses
- : sensor concepts and specifications
- : actuator designs and concepts
- : direct drive and other transmission concepts (belt drive, worm gear, etc.)
- : solutions for simulating high torque requirements
- : software functions and controller strategies.

R&D VEHICLE WITH EXTENSIVE SCOPE

The test rig results can be simulated and tested directly in the R&D vehicle. To test and validate solution concepts and functionalities which cannot be developed in CAE or on the test rig, the R&D vehicle and the steering components are extensively designed in modular form. Based on a "Roding Roadster", ②, a small-scale sports car, the R&D vehicle offers extraordinary design opportunities in terms of the steering gear, steering column and feedback actuator due to its mid-engine concept.

R&D vehicle with steer-by-wire system



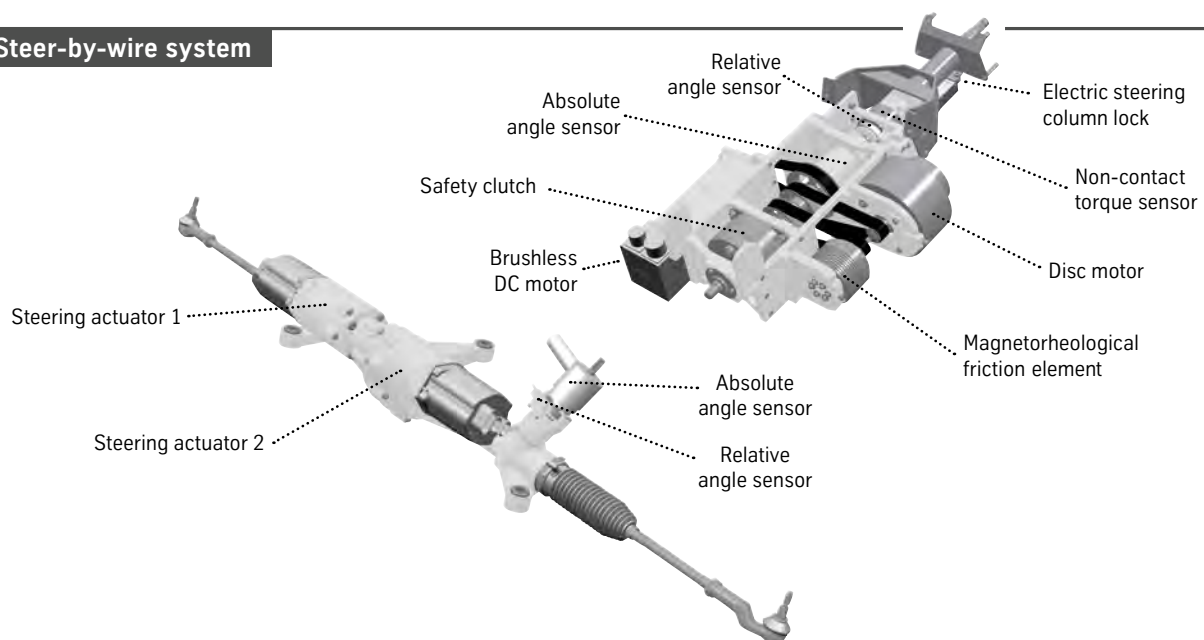
② "Roding Roadster" R&D vehicle

The feedback actuator, ③, is designed in-line with the test rig. In addition to high-precision angle and torque sensors, it allows two different actuators to be compared directly against each other, as they are connected to the steering wheel via an electronically switchable coupling. To prevent an artificial steering feel around the zero position (on-center feel) during straight-ahead driving, a certain level of friction is required in the feedback system. In the R&D vehicle, this can be set using software and is simulated by a specially developed friction element, ④. The friction element

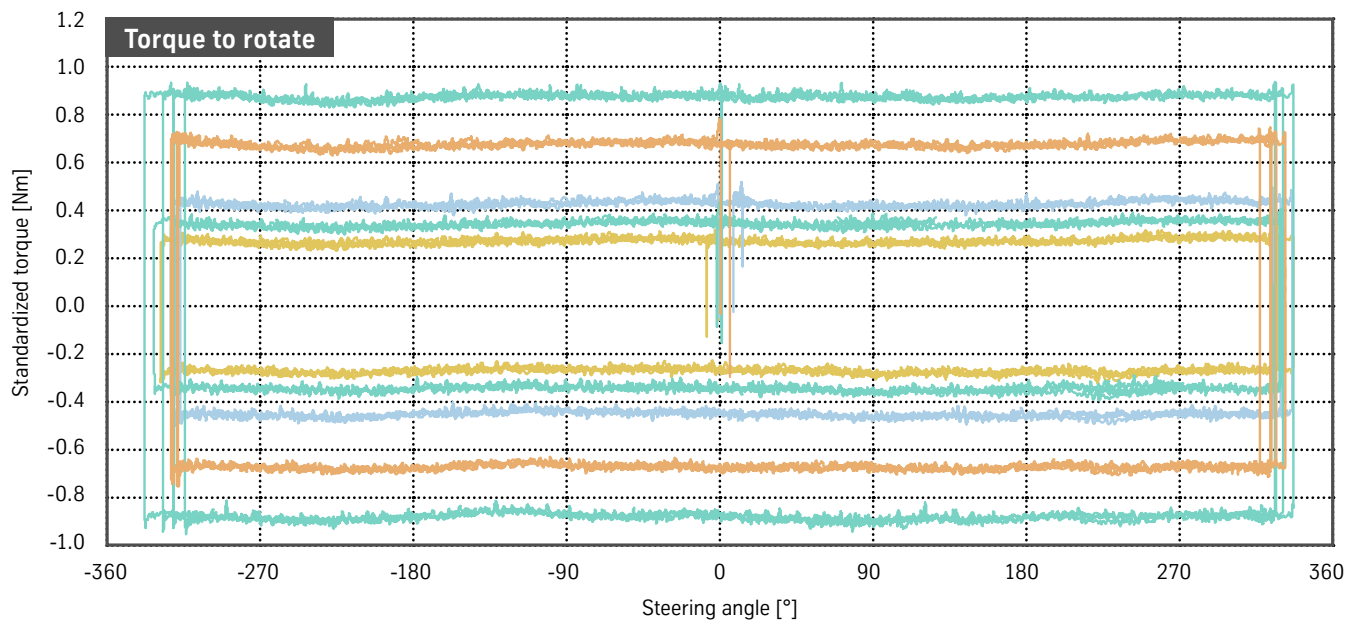
enables the simulation of a homogeneous torque to rotate without stick-slip effects when changing directions. The virtually "mechanical" friction generated in this way can be infinitely adjusted from 0.05 to 10 Nm.

The steering gear is based on a rack EPS system from ThyssenKrupp. With its centrally located ball screw, it allows the analysis of redundant systems with two power packs. This enables different redundant solution and control approaches to be developed and tested

Steer-by-wire system



③ Steering gear (left) with feedback actuator (right)



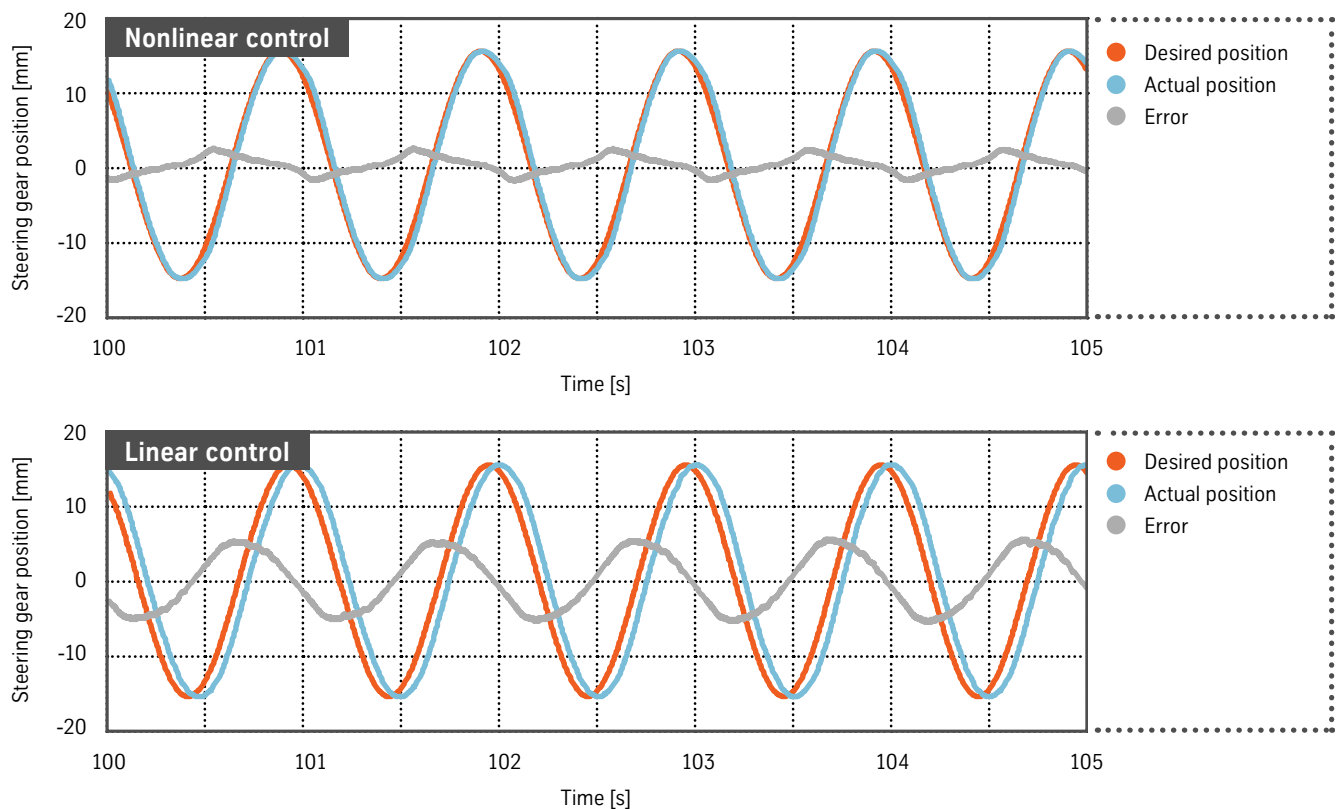
④ Standardized representation of the torque to rotate with varying energization of the magneto-rheological friction element

with one piece of hardware. The power packs can be coupled via a definable stiffness up to and including play or can act independently of each other. To guarantee prototype and failure safety, the feedback

actuator is connected to the steering gear via an actively open mechanical clutch.

In addition to the steer-by-wire-specific sensors, the vehicle is equipped with measurement technology which precisely

registers further signals such as the vehicle speed, lateral acceleration and yaw rate. An AutoBox is used as a real-time system for processing this information and transforming it into corresponding



⑤ Steering gear control

control commands. The test object is equipped with both a CAN and a FlexRay bus system which ensures communication with the steering gear, feedback actuator and vehicle. The overall configuration enables flexible development and testing of various software functions at vehicle level.

STEERING GEAR CONTROL CONCEPTS

The steering gear rack movement control is responsible for precisely following the steering movement desired by the driver in terms of position and speed. Two different control concepts have been developed and applied for this. One is based on the conventional, linear state space control, the other on the extended, nonlinear Lyapunov control. Both concepts are based on the mathematical-physical description of the mechanical steering gear by means of differential equations. The majority of naturally occurring systems are nonlinear, but can be described precisely enough using linear models. However, there are limits. Outside of these, the model is no longer sufficient

and the theoretical behavior deviates excessively from the real behavior. Initial simulations and tests on the test rig show the influence of the nonlinearities in the higher dynamic range of the nominal position, as can be seen in 5.

The described R&D vehicle forms the basis of the methodically oriented procedure for understanding the complex requirements on a steer-by-wire system and developing individual solutions. Only coordinated development steps enable the creation of tailored component requirement specifications and achievement of the maximum cost advantage while simultaneously implementing a natural steering feel.

Redundancies and fall-back levels are also being developed independently of the steering as part of InCar plus. One strategy is torque vectoring as a fall-back level for the steering system. In this, specific drive and braking torques at the wheels "steer" the vehicle. To develop this strategy, ThyssenKrupp has established a simulation environment along with a corresponding vehicle model, and has used these to analyze various strategies and their influence on vehicle response, 6. Initial vali-

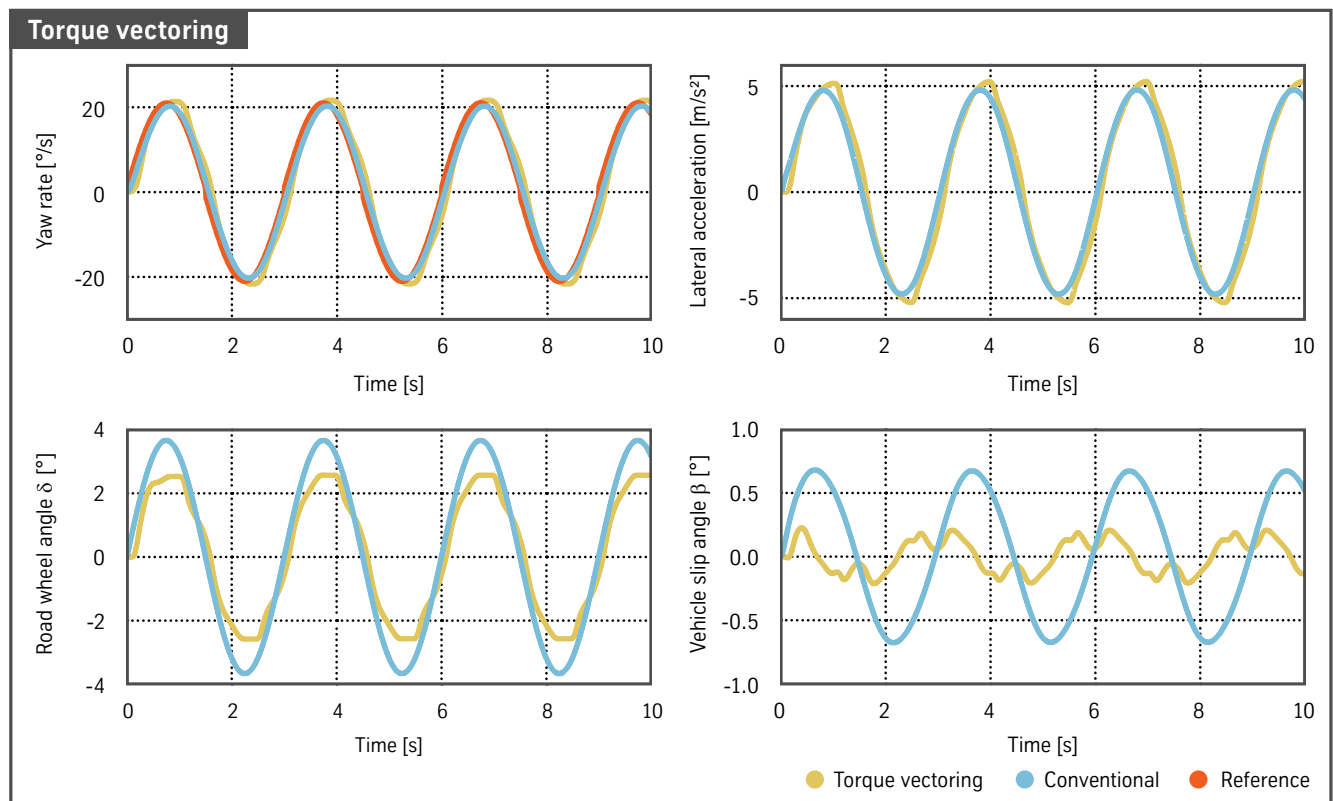
dation of the simulation results is being undertaken on the ETH Zürich Formula Student Race Car, which is equipped with electric individual wheel drive.

FUTURE TASKS

The establishment of this research and development platform is an initial step towards the development of modern steer-by-wire systems. ThyssenKrupp will use this to develop and analyze the following systems and concepts:

- : different concepts for redundancy and functional safety
- : sensor and actuator system concepts and requirements
- : linear and nonlinear controller approaches
- : various approaches and functions for designing the steering feel
- : extended driver support functions
- : cost-optimized component selection.

This list only contains a few of the possible options. Through its work, the project team has generated extensive know-how in the field of steer-by-wire and is implementing this together with vehicle manufacturers.



6 Comparison of a conventional passenger car with standard axle geometry and a vehicle with torque vectoring

BODY





In the InCarplus body subproject, ThyssenKrupp is focusing on economic lightweight design. The complete interaction between new grades of steel, innovative composite materials and modern processing methods such as hot-forming is establishing the basis for light, safe and cost-competitive products. This applies to both classic structural components such as the longitudinal member or B-pillar and closures as well as add-on parts such as the hood or doors. Systems connected to the vehicle body, such as seats and wheels, are also included. In all of these products, high-strength steels achieve excellent results in terms of cost and weight reduction. In addition to material engineering, ThyssenKrupp has also attained extensive expertise in forming and joining technology as well as corresponding system and tool know-how along the value chain and is therefore an outstanding OEM development partner.



BENCHMARK 2.0: THE UPDATED REFERENCE STRUCTURE

For the InCar project in 2009, ThyssenKrupp developed a customer-independent, neutral body-in-white structure which served as a reference body for the various body solution analyses. As part of InCar plus, the list of requirements on development was initially updated and numerous new crash load cases were taken into consideration. Many of the new InCar plus solutions are shown in a demonstrator.

Potential for reducing the weight and costs of body components can only be comprehensively validated in an overall body environment. To update the reference structure to the current technical state of the art, ThyssenKrupp has analyzed the bodies manufactured by various OEMs over the past five years. The information obtained was used to derive competitive values for the stiffnesses and weight of the 2014 reference structure – a representative upper mid-size class body. With a lightweight index of 2.8, for example, InCar was best-in-class in 2009. InCar plus is continuing to maintain this high standard in 2014 with a lightweight index of 2.7. This very good value is essentially based on the improved design of the components, consisting of thin-walled, high-strength steels, in the load paths. InCar plus additionally reflects the market trend and increasingly implements hot-forming as well as high- and ultra high-strength, cold-formable steels, ❶.

The individual solutions in the following articles are always compared with the 2014 reference structure status to reveal the weight, cost or performance advantages. The target specifications include a higher level of maturity in comparison with the solutions already presented in the predecessor project, including the door, hood, B-pillar and longitudinal member. The focus in these areas is placed on new materials as well as innovative concepts and manufacturing techniques. However, new concepts with major potential for economic lightweight design, e.g. a bumper system or an A-pillar, are also presented. Besides body applications, there are also new concepts for cockpit beams, seats and wheels. Particularly cost-competitive lightweight design solutions are presented for seat structures, and as far as wheels are concerned, the focus is not only on lightweight design but also to an equal extent on the second, emotionally important aspect of styling. InCar plus is therefore not only the successor project of InCar but also extends the spectrum of the most extensive research project ever undertaken throughout the ThyssenKrupp Group.

CHALLENGE FROM THE USA

In 2013, America's IIHS (Insurance Institute for Highway Safety) confronted automotive developers with a new crash load case, the small overlap rigid barrier test (SORB). As the new, rigid barrier used in the SORB only covers 25 % of the front end (Euro NCAP: 40 %), it no longer impacts against the level of the lower longitudinal member in the majority of vehicles. As a result, this level absorbs far less kinetic energy, and the barrier deforms the front wheel suspension and then the A-pillar with a high level of kinetic energy, ❷. This new load case gave rise to the complete revision of the front end of the reference structure vehicle from 2009.

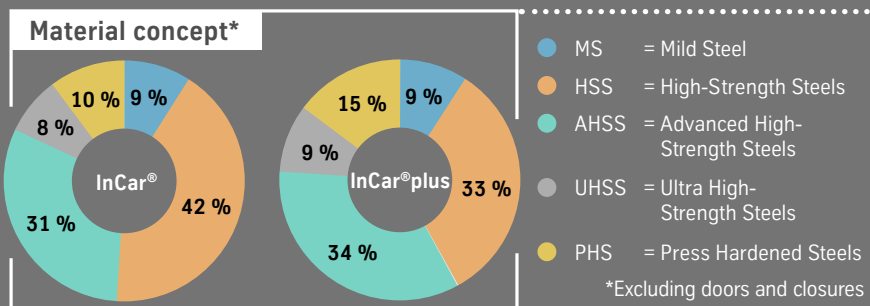
In order to re-integrate the lower longitudinal member into the energy transformation process, the engineers have installed an additional component on the outer side of the lower longitudinal member. With its linear structure, this absorber is supported on the lower longitudinal member; it is impacted by the barrier in the SORB crash and specifically deforms the longitudinal mem-

ber. As a result, firewall intrusion is lower than the permissible maximum values, ❸. The additional InCar plus weight required to fulfill the SORB load case is 8.2 kg.

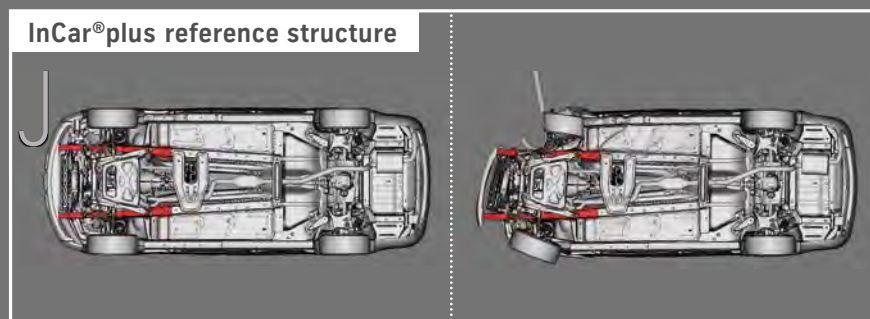
FLEXIBLE BODY-IN-WHITE, COST-EFFICIENT REFERENCE STRUCTURE

Body-in-white production planning for InCar plus is also oriented towards the current, typical automotive standards. One important aspect, for example, is fully automated component supply. As the new reference structure reveals numerous improvements in terms of design and component geometry compared to InCar, a completely new body-in-white line is necessary. The component developers, joining technicians and body-in-white planners began by compiling all of the data on the reference structure. Subsequent manufacturing planning already gives consideration to the integration of the optimized InCar plus components into the new joining processes.

A detailed cost assessment of the various body solutions and the reference

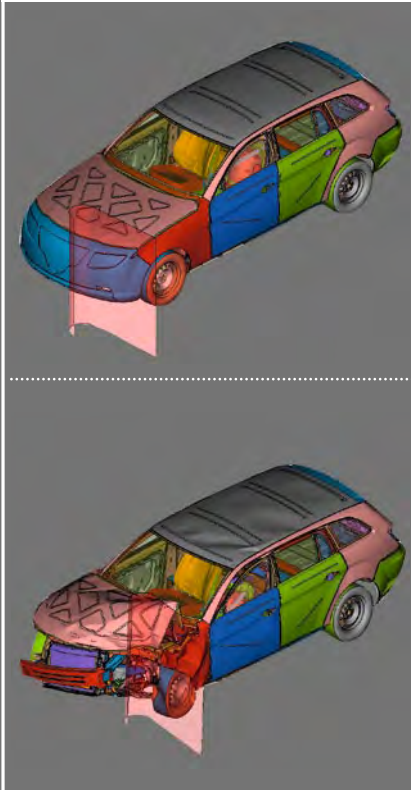


❶ Comparison of the InCar and InCar plus material concepts



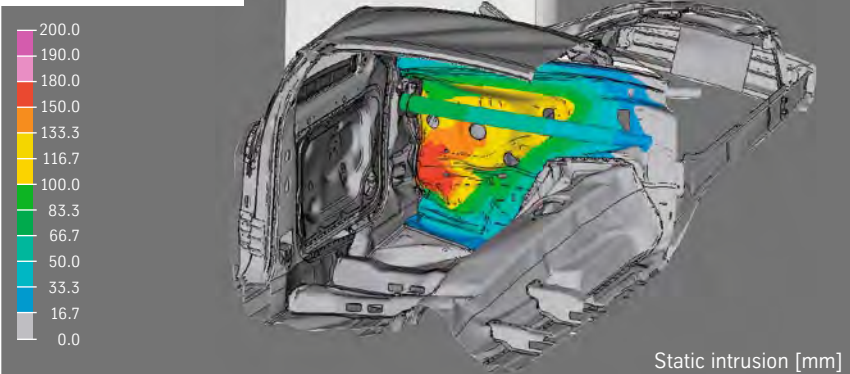
❷ SORB load case for the reference structure without SORB measures

InCar®plus reference structure

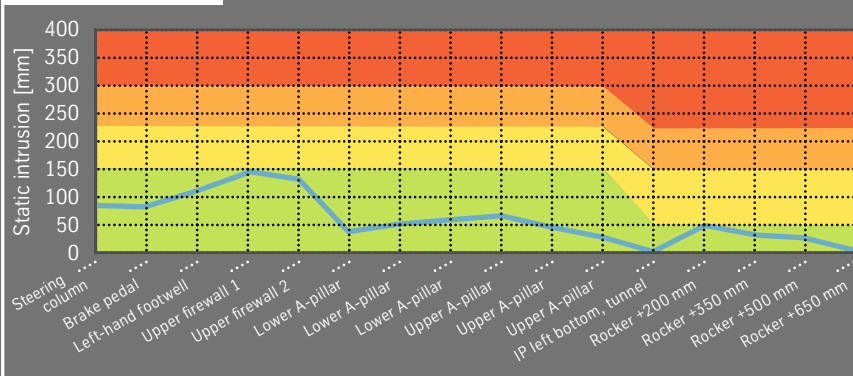


3 InCar plus reference structure with SORB measures

Firewall intrusion



Static intrusion



structure flanks the technical further developments implemented within InCarplus. Production planning is based on the following scenario: 200,000 vehicles per year as before; the production period is shortened from eight to six years. The cost-effectiveness calculation is based on a “green field” approach, a realistic manufacturing plant operating rate and the wage level usual in Germany. The manufacturing costs are determined using an internal calculation tool, the material costs on the basis of material prices at the beginning of 2014.

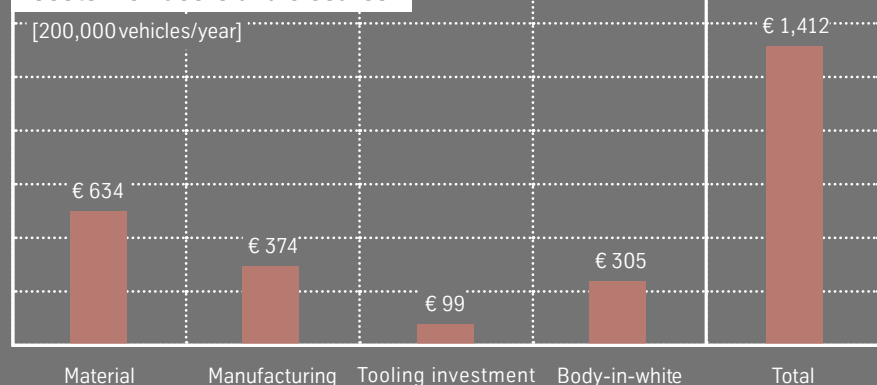
The investment amounts for tools and body-in-white lines are provided by experts within ThyssenKrupp and have been converted into costs per vehicle with corresponding interest in the calculation. In addition to direct manufacturing costs (material, hourly machine rate, personnel), the scope taken into account in the calculation also includes percentage surcharges for material and manufacturing overheads. Inter-company logistical costs and profits are not included. All cost

data are customer neutral and serve to compare quality.

On this basis, costs of € 1412 arise for the body-in-white, doors, closures and bolt-on parts for the InCar plus body-in-white, 4. The costs are comparable with those of the InCar reference structure. The tool (allocation) and body-in-white

costs have risen slightly due to shortening the production period to six years, while the material and manufacturing costs are slightly lower. The outlined costs are extensively dependent on the selected boundary conditions. OEMs will arrive at varying results due to their specific manufacturing process.

Costs incl. doors and closures



4 Distribution of the total InCar plus reference structure costs

NEW LIGHTWEIGHT DESIGN FOCUS: THE COCKPIT BEAM

The lightweight solutions presented back in 2009 are being further developed by ThyssenKrupp as part of the InCar plus project. In addition, the second project from 2014 is also offering new solution approaches, e.g. a cockpit beam which is around 3.4 kg lighter than current steel solutions. With lightweight design costs of € 5.30/kg, it offers easily accessible potential for saving weight.

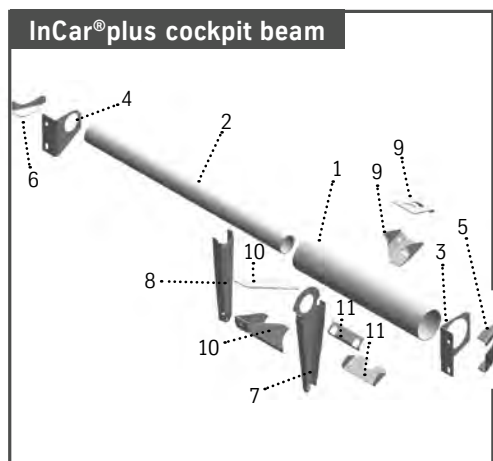
While updating the InCar plus reference structure, the body and near-body components such as closures and add-on parts were investigated as regards their potential weight savings. One component in which lightweight measures are especially worthwhile is the cockpit beam. To obtain an overview of the trends and products in this field, the ThyssenKrupp engineers compared almost 300 different cockpit beams. Important parameters include the use of material, the connection and support points, and weights. Steel is the preferred material in 64 % of the investigated cockpit beams, followed by die-cast magnesium and aluminum. The average weight of the investigated cockpit beams is 7.5 kg (steel), 4.5 kg (aluminum) and 3.5 kg (magnesium).

To reveal the weight advantages of magnesium sheet, ThyssenKrupp developed an alternative concept using flat magnesium products. This new cockpit beam consists of a twin-tube system with additional magnesium sheet components and is joined by means of MAG welding, ❶.

The cockpit beam's usage characteristics are validated virtually. For the simulations, a widely used steering column and a substitute mass for the steering wheel are added to the cockpit beam. Integration into a rigid frame guarantees a manufacturer-neutral installation situation. Global natural frequencies include the lateral mode with 42.0 Hz and the vertical mode with 45.0 Hz. The high natural frequencies reflect the cockpit beam's good stiffness-to-weight ratio. At

3 Hz, it is additionally guaranteed that the spread between the first global modes is sufficiently large. As further verification of the usage characteristics, a vertical load of 100 kg is applied onto the steering wheel. At 95 MPa, the stresses induced in the cockpit beam are around 44 % less than the yield stress of Mg AZ31. This therefore guarantees that no plastic deformation will occur during daily use.

The magnesium sheet cockpit beam developed in the InCar plus project weighs 2.4 kg. If this is compared with an optimized steel cockpit beam weighing 5.8 kg, the lightweight design costs amount to € 5.30/kg. Magnesium sheet components therefore offer great potential for reducing weight in vehicles.



❶ Magnesium sheet cockpit beam

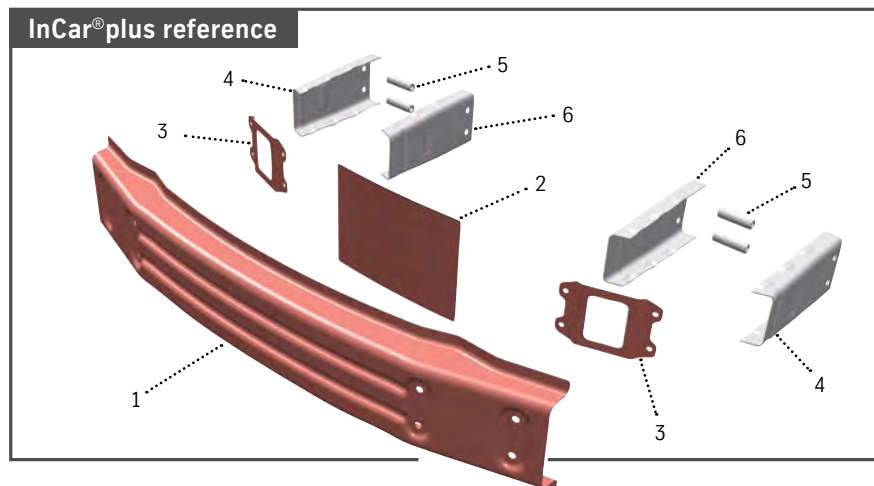
No	Part	Material	Thickness
1	Cross member left	AZ 31	2.30 mm
2	Cross member right	AZ 31	1.00 mm
3	Bracket cross member left	AZ 31	2.50 mm
4	Bracket cross member right	AZ 31	1.00 mm
5	Reinforcement bracket cross member left	AZ 31	2.50 mm
6	Reinforcement bracket cross member left	AZ 31	1.00 mm
7	Tunnel support left	AZ 31	1.30 mm
8	Tunnel support right	AZ 31	1.00 mm
9	Brackets steering column	AZ 31	2.50 mm
10	Firewall supports	AZ 31	2.50 mm
11	Brackets steering column front	AZ 31	2.50 mm

BUMPER SYSTEMS OPTIMIZED IN TERMS OF MANUFACTURING PROCESS, WEIGHT AND COSTS

Bumpers still offer high lightweight design potential in the vehicle front end. A new bumper system with a hot-formed steel crash beam which is 19 % lighter than the reference solution with comparable costs is being developed as part of InCar plus. This means that the weight of average aluminum solutions will be achieved at significantly lower cost. Modular and roll-formed sectional crash beams have also been developed. These are up to 17 % lighter and offer the advantage of cross-fleet flexibility. Thanks to new grades of steel, weight reductions of around 13 % are possible in the crash boxes. The results are rounded off by a bumper concept which can be easily integrated into existing vehicle structures and coordinated with the IIHS small overlap rigid barrier (SORB) load case.

The reference bumper system consists of a hot-formed crash beam with closing plate and crash boxes mounted using connecting plates, inserted into the longitudinal members and bolted there, ❶. This corresponds to the state of the art in 2014. Due to the reference vehicle's gross weight of around 1860 kg, the crossmember consists of high-strength manganese-boron steel MBW 1500 with a sheet thickness of 2.0 mm. The crash boxes are formed from two laser welded half shells (DP-W 330Y580T, sheet thickness 2.2 mm). The closing plate improves system stability in punctiform load cases such as the mast impact. The reference solution therefore has a total weight of 10.21 kg.

The design of the InCar plus concepts pays particular attention to fulfillment of the diverse crash load cases in combination with technical forming feasibility. There are conflicts between a crash-optimized design and what is feasible in forming technology terms. For example, a component geometry which would not have been considered possible prior to



No.	Part	Material	Coating	Thickness	Weight
1	Crash beam	MBW® 1500	AS150	2.00 mm	5.48 kg
2	Closing plate	CR300LA	GI40	1.00 mm	0.51 kg
3	Crash plates	CR240LA	GI40	2.00 mm	0.44 kg
4	Crash box shells outer	DP-W® 330Y580T	EG53	2.20 mm	1.50 kg
5	Bushing for crash boxes (4 pcs)	C22	U		0.44 kg
6	Crash box shells inner	DP-W® 330Y580T	EG53	2.20 mm	1.60 kg
Total weight per vehicle (incl. 0.24 kg fastening materials)					10.21 kg

❶ Reference bumper system

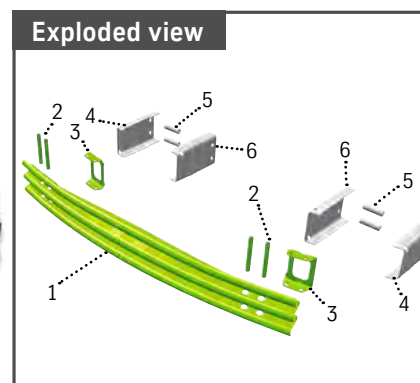
the start of the project has been achieved for the open crash beam through optimization loops. Further objectives include the minimal overall weight of the bumper solutions, low system costs and simplest possible integration into existing body-in-white and manufacturing structures. To validate the virtual results, the bumper systems are subjected to an extensive test program.

The crash requirements on a bumper system are very complex. On one hand, the system must be matched to the load cases with low impact speed such as the RCAR bumper test and the insurance classification test AZT up to 15 km/h. On the other hand, it must also withstand the Euro NCAP ODB load case with an impact speed of 64 km/h.

For the RCAR bumper load case, the maximum intrusion in the direction of the engine is limited for the virtual design so that the radiator system, the headlamps and the adjacent mounting structure do not have to be exchanged after a minor collision. The requirements defined for the Euro NCAP ODB load case are more stringent than those of the US NCAP load case, which is why it is regarded by OEMs as the crucial load case for development. The manufacturers each define different test conditions for the central mast impact load case, which was also tested. As part of the solutions analyzed here, the test is regarded as passed when a sufficiently high force level is attained and the implemented crash beam's material does not fail.

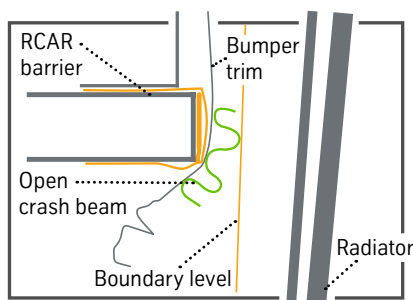
OPEN CRASH BEAM

The open crash beam solution consists of an undulated, stamped basic body and consciously forgoes reinforcing components such as closing plates, ❷. The beam's performance is obtained solely from its geometric design and material characteristics. The crash boxes are bolted to the crash beam via connecting plates; spacer bushings accommodate the bolts. A less expensive welded connection can be used for other design situations between the crash box and longitudinal member. In addition to the proven MBW 1500 material, hot-forming steels MBW 1900 and Tribond 1400 plus cold-formed materials such as iron-manganese steels or dual-phase steel DP-K 780Y1180T HF (this steel is in development) are being investigated for the



No.	Part	Material	Coating	Thickness	Weight
1	Open crash beam	MBW® 1500	AS150	1.70 mm	4.29 kg
2	Bushing for crash beam (4 pcs)	S355J	U		0.16 kg
3	Crash box connecting plates	CR300LA	GI40	2.50 mm	0.42 kg
4	Crash box shells outer	DP-W® 330Y580T	EG53	2.30 mm	1.30 kg
5	Bushing for crash boxes (4 pcs)	C22	U		0.44 kg
6	Crash box shells inner	DP-W® 330Y580T	EG53	2.30 mm	1.36 kg
Total weight per vehicle (incl. 0.28 kg fastening materials)					8.25 kg

❷ Components of the open crash beam and their characteristics



❸ Results of the RCAR bumper test crash simulation; cross-section with boundary level and test setup



crash beam. The results achieved with MBW 1500 will be presented in detail in the following.

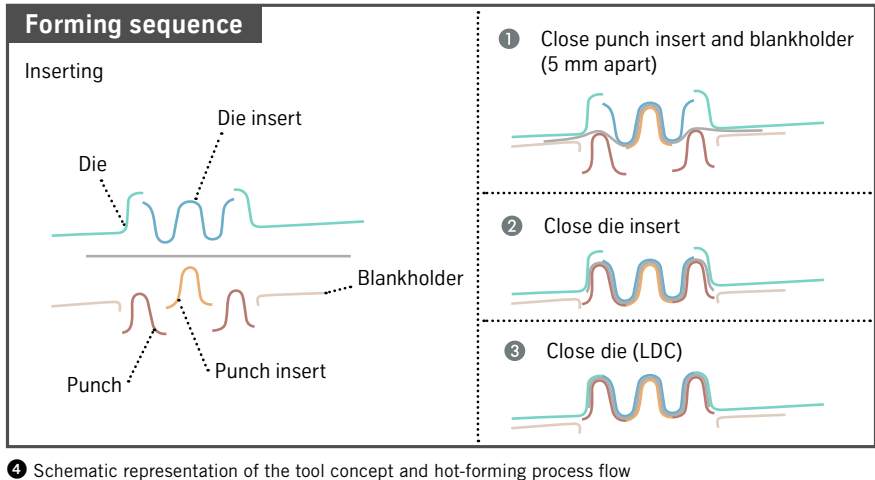
Thanks to its undulating form, the crash beam forms six bridges in the barrier impact direction and therefore offers correspondingly high bending stiffness. The depth of the bridges increases to the center to offer maximum resistance to deflection and buckling at the impact point. In the RCAR bumper test, the barrier impacts the crash beam above the center crash box plane due to the specified height of the longitudinal members, thereby generating additional load torque around the vehicle's transverse axis, ❸. Stiffening plates specifically integrated into the base of the undulating form increase the beam's stiffness against bending up in this case. The beam's

global curvature forwards, the depth of the bridges and the number and shape of the stiffening plates enable the sheet thickness to be reduced to 1.7 mm due to their specific interaction. This leads to a weight advantage of 2 kg in comparison with the reference system.

Hot-forming enables very high levels of forming with very low springback (deviations from the tool geometry), enabling complex component forms to be implemented. The crash beam shape derived from the analyzed crash load cases is very demanding in terms of forming technology, because in combination with its profile depth and the integrated stiffening plates, the beam's undulating shape normally requires several drawing stages. If at all, this would only be achievable with great effort in

hot-forming. However, ThyssenKrupp has succeeded in generating the complex component geometry for hot- and cold-forming steels with an intelligent tool concept and with just one press stroke.

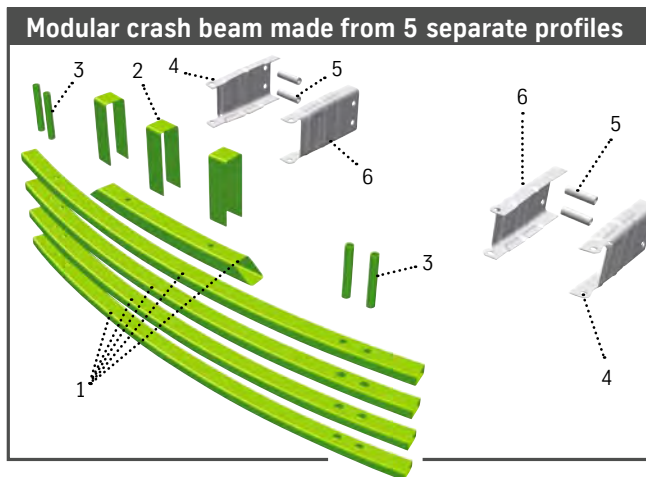
To achieve the actual forming process required for hot-forming with two to three tool stages, a new five-part tool concept with coordinated kinematics was developed. This produces the complex component geometry in one process. On running through the individual process steps, forming is carried out with several opposing drawing directions. The upper part of the tool is two-part and the lower part three-part to enable the undulations to be formed gradually from the inside out. The blank is drawn into the mold solely through the relative position of the individual parts of the tool to one another and can therefore be finely adjusted in prototyping. This particularly includes



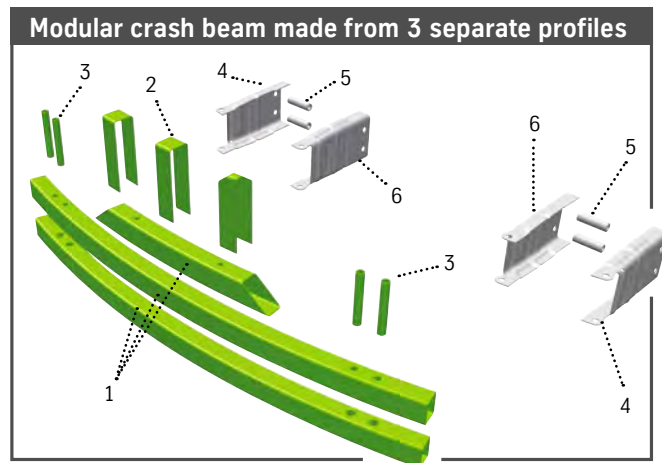
④ Schematic representation of the tool concept and hot-forming process flow

precise dosing of the surplus material integrated via the stamping areas on closing the die insert, ④.

In all, this newly developed process has enabled material thinning to be kept below 25 % even in severely stressed

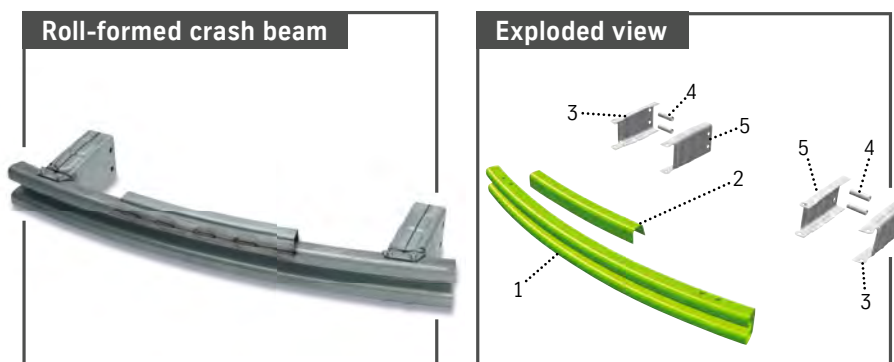


No.	Part	Material	Coating	Thickness	Weight
1	Modular crash beam (5 profiles)	DP-K® 590Y980T	GI40	1.00 mm	4.47 kg
2	Sheet metal clips	CR300LA	GI40	1.00 mm	0.27 kg
3	Bushing for crash beam (4 pcs)	S355J	U		0.28 kg
4	Crash box shells outer	DP-W® 330Y580T	EG53	2.30 mm	1.40 kg
5	Bushing for crash boxes (4 pcs)	C22	U		0.44 kg
6	Crash box shells inner	DP-W® 330Y580T	EG53	2.30 mm	1.48 kg
Total weight per vehicle (incl. 0.52 kg fastening materials)					8.86 kg



No.	Part	Material	Coating	Thickness	Weight
1	Modular crash beam (3 profiles)	DP-K® 590Y980T	GI40	1.30 mm	4.46 kg
2	Sheet metal clips	CR300LA	GI40	1.00 mm	0.30 kg
3	Bushing for crash beam (4 pcs)	S355J	U		0.28 kg
4	Crash box shells outer	DP-W® 330Y580T	EG53	2.30 mm	1.40 kg
5	Bushing for crash boxes (4 pcs)	C22	U		0.44 kg
6	Crash box shells inner	DP-W® 330Y580T	EG53	2.30 mm	1.48 kg
Total weight per vehicle (incl. 0.52 kg fastening materials)					8.88 kg

⑤ Modular bumper systems consisting of five (left) and three separate profiles (right)



No.	Part	Material	Coating	Thickness	Weight
1	Roll-formed crash beam	MS-W® 900Y1180T	EG53	1.60 mm	4.59 kg
2	Top part crash beam	MS-W® 900Y1180T	EG53	1.60 mm	0.64 kg
3	Crash box shells outer	DP-W® 330Y580T	EG53	2.30 mm	1.40 kg
4	Bushing for crash boxes (4 pcs)	C22	U		0.44 kg
5	Crash box shells inner	DP-W® 330Y580T	EG53	2.30 mm	1.48 kg
Total weight per vehicle (incl. 0.24 kg fastening materials)					8.79 kg

6 Crash beam as roll-formed section

areas. The clearance holes for the crash box fastening bushings are integrated into the blank; final trimming is carried out using a laser after hot-forming and hardening.

MODULAR CRASH BEAM

Increasing variant diversity in the OEMs' model ranges is necessitating new, modular concepts. Attractive lightweight design in combination with easily variable manufacturing methods as a common basis for all vehicles is a convincing approach. The modular crash beam is one such solution. It is up to 17 % lighter and, depending on the number of module brackets, up to 5 % less expensive than the reference crash beam. Constructed using the simplest possible sub-components, the modular systems meet all of the crash requirements. They are constructed from three or five separate profiles stacked on top of each other, 5. The profiles have a simple rectangular cross-section and are bent in-line with a constant radius after roll-forming to save costs.

To achieve the necessary coverage in the RCAR bumper crash load case, the profile system is closed at the top with a shorter profile top part. Due to reasons of stability, the profiles are both adhesively bonded to each other and joined with

three welded sheet metal clips. Both conventional welding processes such as MIG welding and further developed resistance spot welding on one side are used. In combination with the double-walled bridges, the profile system therefore develops outstanding stiffness in intrusion load cases. The crash boxes are bolted to the profile system using spacer bushings and without an additional connecting plate.

The advantage of the modular structure is patently clear: the bumper concept can be flexibly coordinated to variables such as the vehicle weight or package through variation of the number of profiles, sheet thickness, steel grade and/or profile cross-section. A mixture of various steels and sheet thicknesses in one module package is also conceivable. The maximum weight reduction of around 17 % is achieved with a system of five profiles consisting of MBW 1500 in the lower area and DP-K 590Y980T in the upper area. However, solutions manufactured throughout with the DP-K 590Y980T material (five profiles with a thickness of 1.0 mm or three profiles with a thickness of 1.3 mm) are also characterized by a weight advantage of more than 13 % in comparison with the reference. Compared with the reference, the costs fluctuate between moderate lightweight design costs of € 0.80/kg for the system consisting of five profiles

and a cost advantage of around 5 % for the system consisting of three profiles.

CRASH BEAM AS ROLL-FORMED SECTION

The InCar plus crash beam consisting of a roll-formed section is characterized by its simple structure and lightweight potential of 14 % with a cost advantage in comparison with the reference solution. It consists of ultra high-strength MS-W 900Y1180T steel with a thickness of 1.6 mm, a top part for the necessary coverage in the RCAR bumper test and the crash box, 6. This concept impresses through the simplicity of manufacturing its individual components. The crash beam's B-shaped cross-section increases stiffness in the intrusion direction in the RCAR bumper test and the mast impact load test, ensuring that all of these tests are also passed.

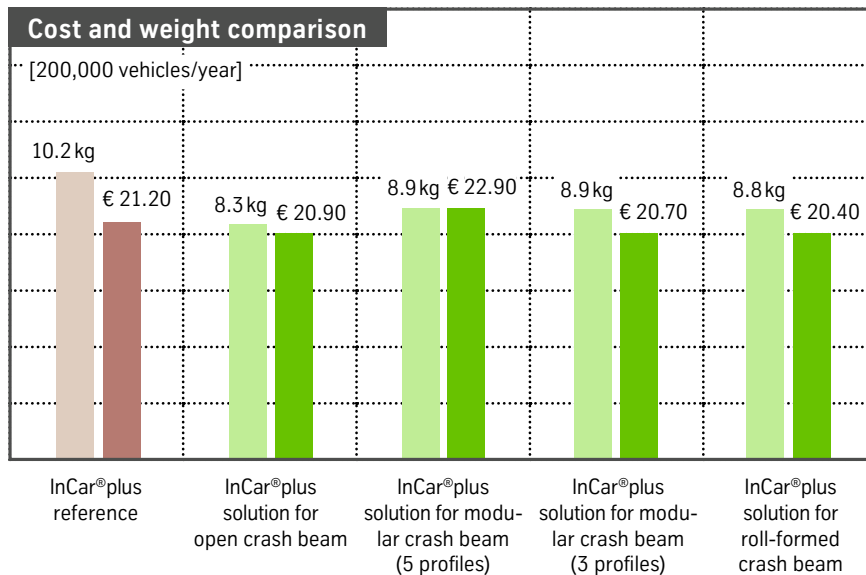
COMPARISON OF CRASH BEAM CONCEPT COSTS

The crash beam concept cost comparison is based on the quantities defined in InCar plus, 7. Both manufacturing of the component parts and their assembly to form systems ready for installation have been checked as regards feasibility. The necessary manufacturing systems correspond to realistic specifications. An analysis of the required tooling investments reveals the advantages of flexible, modular crash beams in comparison with individual concepts which are transferred to different vehicle concepts.

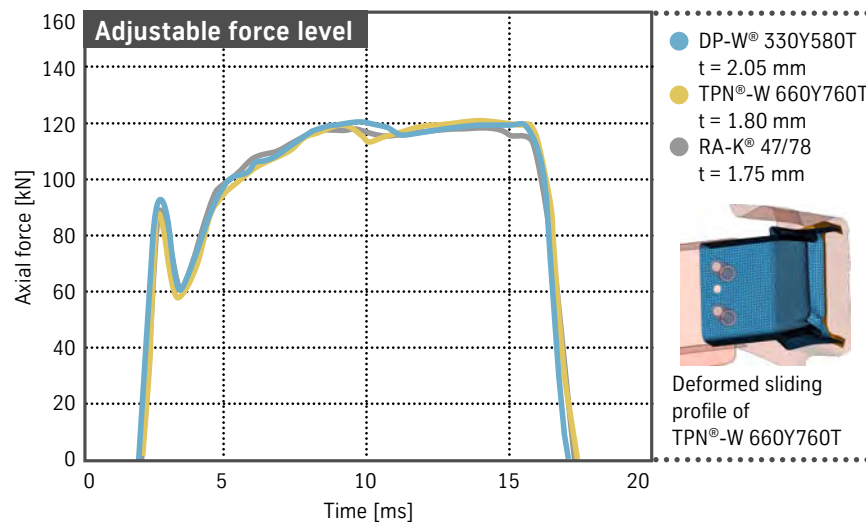
Crash beams consisting of various shell components also require new tools for each new geometry. In contrast, a modular system structure with identical manufacturing systems is suitable for beams in various vehicle segments, because it enables the sheet thickness, length, curvature and stacking of the separate profiles to be scaled without major additional effort. Depending on quantity scenario, this leads to an additional advantage – despite the increased assembly effort due to the higher number of component parts.

CONCEPTS FOR THE CRASH BOXES

Apart from end trimming, the crash boxes are identical for all of the above mentioned crash beams. They consist of



7 Cost and weight comparison of the investigated crash beam systems



8 Deformed sliding profile and axial force curve for various steel grades and sheet thicknesses

that a sliding profile can be adjusted to different force levels with relative ease. Thanks to extensively constant energy absorption over the deformation path, sheets thinner than those used in a collapsible box are possible. With the same steel grade, the sheet thickness can be reduced by 0.25 mm (11 %); on use of higher strength materials such as CP-W 660Y760T or RA-K 47/78, it can actually be reduced by up to 0.55 mm (24 %).

INTEGRATION OF THE ABSORBER

The functional principle of the absorber used in the reference structure is also integrated into the following virtually studied bumper concept. In the IIHS SORB load case, the 25 % barrier does not normally impact the lower longitudinal member. However, the absorber involves the supporting vehicle front end structure in energy absorption and therefore limits passenger cell deformation (also see article “Benchmark 2.0: the Updated Reference Structure” from page 86). While the absorber wedge is welded onto the longitudinal member in the reference, it is connected directly to the transverse crash beam in the virtual bumper concept and can therefore be implemented as an add-on part without intervention into the body-in-white. In this manner, the absorber reduces fire-wall intrusion by 19 % in comparison with the reference solution. At the same time, this solution is lighter and therefore reduces the additional weight caused by the SORB load case by around 8 % with comparable costs.

DP-W 330Y580T material, have 2.3 mm thick sheets and act as collapsible boxes. The axial force which occurs in the AZT is absorbed by the beading profile and the sheet thickness so that no plastic extension >2 % occurs in the longitudinal member. The required deformation space corresponds to that of the reference. Use of higher strength materials such as three-phase steel TPN-W 660Y760T or complex-phase steel CP-W 660Y760T enables up to 13 % lower sheet thicknesses and further related weight reductions.

A second variant of the crash boxes, which functions according to an entirely different profile, is the sliding profile,

also called the sliding absorber box, 8. Even sinking of the staged crash box areas into one another rather than a collapsing process dissipates the impact energy in this case. This process leads to material deflection via a continuous S-shaped fold and thus a very even force level in the axial direction.

This crash box variant's half shells are produced in a three-stage process. On closing the upper part against the bottom part of the tool, the bottom of the component is stamped; the component's lateral flanges are freely raised further on in the process.

Investigations involving various material grades and sheet thicknesses show

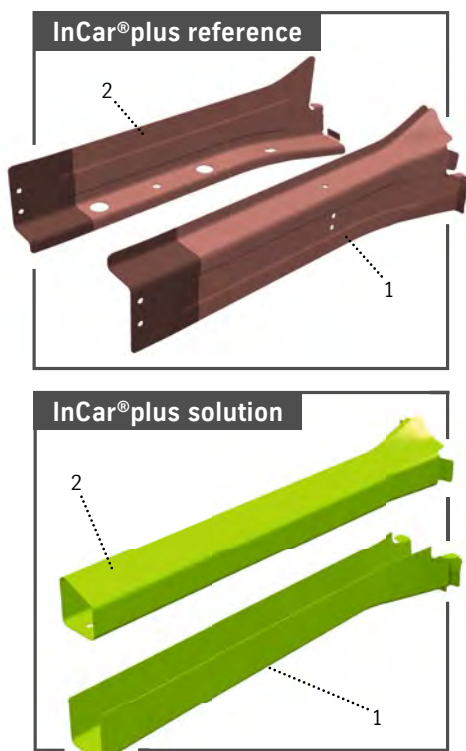
LIGHTWEIGHT LONGITUDINAL MEMBERS THANKS TO OPTIMIZED MANUFACTURING PROCESSES

The InCar plus longitudinal member is a completely new type of steel multi-section profile. Manufacturing technologies developed for use in production are being implemented in the combination of a deep drawn shell part and a T³ profile; these technologies enable the production of high-precision components. Due to the modular structure, such a system can be easily adapted to other vehicle classes. Based on the example of the longitudinal member, weight and costs can be reduced by 23 % and 10 % respectively with convincing crash, stiffness and global eigenmode performance at the same time. With an especially progressive material combination, the weight advantage actually increases to as much as 31 % with a continued cost advantage of 8 %.

The lower longitudinal members are central elements of the front structure of each vehicle and contribute extensively to passenger cell protection in the event of an accident in the main load path. The

longitudinal members additionally influence the overall vehicle's torsional and bending stiffnesses. Longitudinal members are usually deep drawn shell parts with mounting points for subframes, the

chassis and, under certain circumstances, engine mounts. Lateral bulkheads, reinforcement plates and a coordinated beading profile optimize crash performance and stiffness.

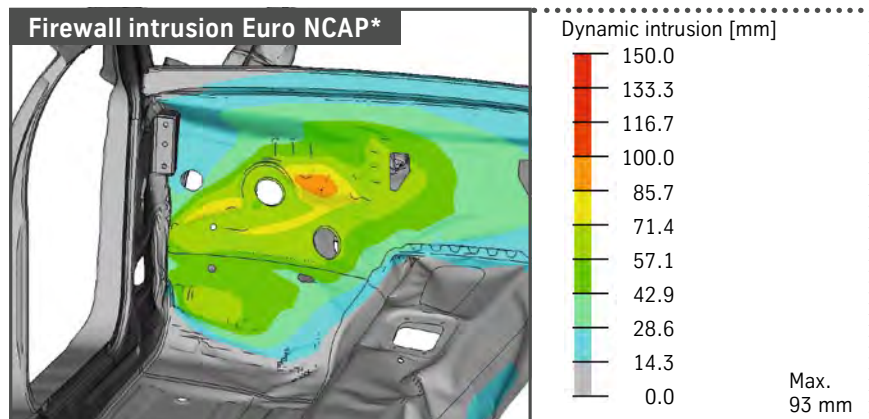
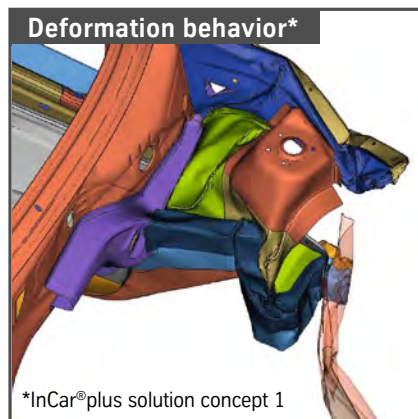


1 InCar plus reference longitudinal member (top) and the developed steel multi-section profile (bottom)

No.	InCar [®] plus reference	Material	Coating	Thickness	Weight
1	Longitudinal member left outer	DP-K [®] 440Y780T	GI40	2.00 mm / 1.80 mm	3.75 kg
2	Longitudinal member left inner	DP-K [®] 440Y780T	GI40	2.00 mm / 1.80 mm	3.81 kg
Total weight per vehicle					15.12 kg

No.	InCar [®] plus solution concept 1	Material	Coating	Thickness	Weight
1	Longitudinal member left bottom, U-shaped shell	CP-W [®] 660Y760T	EG53	1.50 mm	2.98 kg
2	Longitudinal member left top, T ³ profile	MHZ 500	GI40	1.40 mm	2.85 kg
Total weight per vehicle					11.66 kg

No.	InCar [®] plus solution concept 2	Material	Coating	Thickness	Weight
1	Longitudinal member left bottom, U-shaped shell	DP-K [®] 700Y980T	GI40	1.40 mm	2.78 kg
2	Longitudinal member left top, T ³ profile	CP-K [®] 570Y780T	EG53	1.20 mm	2.44 kg
Total weight per vehicle					10.44 kg



② Deformation behavior and firewall intrusion in the Euro NCAP load case with deformable barrier

The objectives when developing new longitudinal members are weight and cost reduction while maintaining performance. Manufacturing focuses on simple assembly of the longitudinal member unit and ease of integration into the body-in-white (BIW).

The reference longitudinal members represent the current state of the art and are assembled using two deep-drawn L-shaped shells, ① (top left). The crash boxes are inserted into the longitudinal member and are bolted there. Support bushings for connection to the chassis are supported on two bulkheads, thus achieving the required local stiffness. The reference structure already gives consideration to the new IIHS load case SORB (see article “Benchmark 2.0: the Updated Reference Structure” from page 86).

The InCar plus longitudinal member, ① (bottom left), consists of a closed T³ profile and an underlying U-shaped shell. The multi-section profile not only saves weight; thanks to its longitudinal separation it also offers better access for joining reinforcement components prior to assembling the longitudinal member's subassembly in comparison with one-piece profile solutions. This enables the two axle mountings to be easily fixed in position in the U-shaped shell by means of resistance spot welding. To adjust the local stiffnesses, the U-shaped shell's sheet is thicker than that of the T³ profile. The hole pattern, center bridge position and wall thickness as well as the choice of the materials used are dependent on the weight of the vehicle.

VIRTUAL CRASH TESTS SUCCESSFULLY COMPLETED

Among other aspects, automotive manufacturers design the vehicle structures on the basis of AZT crash repair tests. Insurance companies assess damage to the vehicle in crash tests and undertake model class classification based on the resulting repair costs. No plastic expansion >2 % should therefore occur in the vehicle structure at low impact speeds.

At higher speeds, the main load path is designed such that the impact energy is transformed into plasticity so that the passenger cell is deformed as little as possible. The test used by automotive manufacturers is the Euro NCAP load case with deformable barrier, the requirements of which are more stringent than those of the US NCAP load case. Due to the barrier coverage of just 25 %, the requirements made on the vehicle structure by the small overlap rigid barrier test developed by the IIHS are especially demanding.

The steel multi-section profile was studied on the basis of these load cases. In the Euro NCAP load case with deformable barrier, the longitudinal member exhibits the desired buckling behavior, while the center bridge contributes extensively to energy absorption, ②. As in the SORB load case, the intrusion values lie below the defined limit values. With plastic expansion of less than 2 % in the load-bearing vehicle structure, the AZT load case is also successfully withstood.

The longitudinal members exert a major influence on global bending and torsional stiffnesses as well as global eigenmodes. To further ensure comparability with the reference, the conceptual longitudinal member also has approximately the same dimensions. It nevertheless achieves global stiffnesses which are higher than required. The first global eigenvalue surpasses the reference's performance; the desired spread of 3 Hz between the global modes remains guaranteed. Thanks to the



③ T³ press adapter: springback-free holding of the U-shaped shell through displaceable walls

chassis mountings connected to the center bridge, the local stiffnesses are higher than the required values throughout.

ECONOMIC T³ MANUFACTURING PROCESS

Implementation of the T³ technology in production is focused on process design and was therefore also taken into consideration throughout prototyping. Three process steps are basically required: blank cutting, U-forming and O-forming with welding flange production integrated into the process. The manufacturing process is completed by joining the profile edges using laser beam welding. Production-capable clamping and welding units are also available for this.

The T³ longitudinal member profile prototype is produced in a so-called T³ press adapter on a conventional deep-drawing press. The adapter's advantage arises from the tool framework provided for automating forming. The tools can be inexpensively exchanged for new profile forms. One feature of the process is the fact that the U form remains in the lower die and is therefore positioned beneath the O tool form without springback, ③. This guarantees process-consistent closure and sizing of the profile. Besides the MHZ 500 steel grade used in material concept 1, CP-K 570Y780T was also tested during prototyping to verify feasibility. Volume production with the T³ press adapter is economic for small to medium batch sizes. The principle can be transferred to transfer presses for large quantities.

U-SHAPED SHELL MANUFACTURING

Springback compensation measures are often carried out iteratively on the trimmed component. If it is no longer possible to ensure the component's dimensional accuracy using add-ons, particularly in the case of higher strength materials, elastic springback has to be laboriously compensated in a subsequent process. While stiffening areas already integrated into the component design reduce rib springback, they do lead to premature buckling of the component on axial loading as initial beading. This instability could only be compensated with thicker metal sheets and thus more weight.

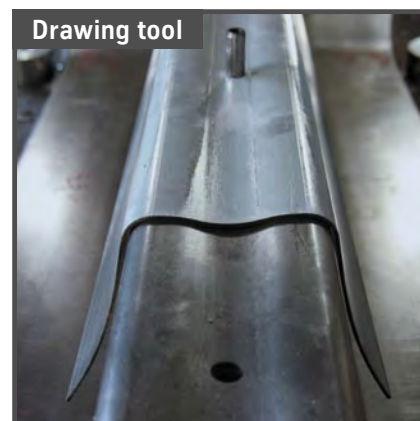
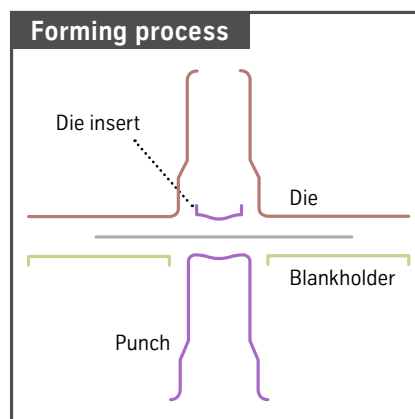
If the number of trimming operations within a conventional process chain can be reduced, maintenance effort, investment costs and energy requirements are cut down. The longitudinal member lower shell is therefore manufactured using sizing deep-drawing with reduced trimming. The starting point is a minimal form blank which already has its final contour in the trimming-free area. This can significantly reduce the use of material through optimized nesting. In the first process step, the minimal form blank is initially used to produce a pre-form without springback compensation through deep-drawing. The drawing part is enlarged by the upsetting allowance required for sizing. This is achieved by extending the ribs and wave-like shaping of the bottom.

So that components with a welding flange can also be manufactured in this way, ThyssenKrupp has realized both the flange-free variant of the U-shaped shell required for the steel multi-section

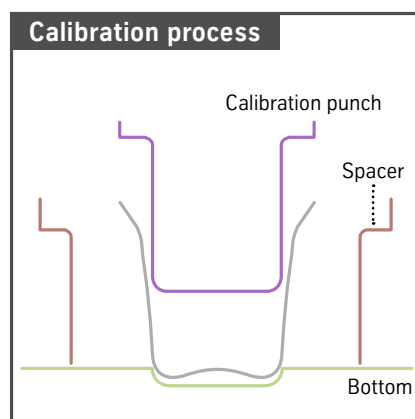
profile and a variant with a stepped welding flange in one tool set. The feasibility of this procedure was also tested for the additional material grades MHZ 500 and DP-K 700Y980T.

Without the otherwise obligatory edge trimming, the contour of the pre-drawn part has to correspond as precisely as possible to the geometry required for subsequent sizing. Process-related form deviations must be minimized. This necessitates a modified drawing process. During forming, a die insert secures the blank to prevent it from slipping. An enlarged drawing gap and the blankholder's permanent and also enlarged distance from the die additionally ensure even drawing conditions. This minimizes the influence of tool tolerances, tool wear and batch fluctuations on the sheet metal, ④.

In the subsequent sizing stage, compressive stress overlay through upsetting compensates the form deviations that occur during drawing. Lateral and



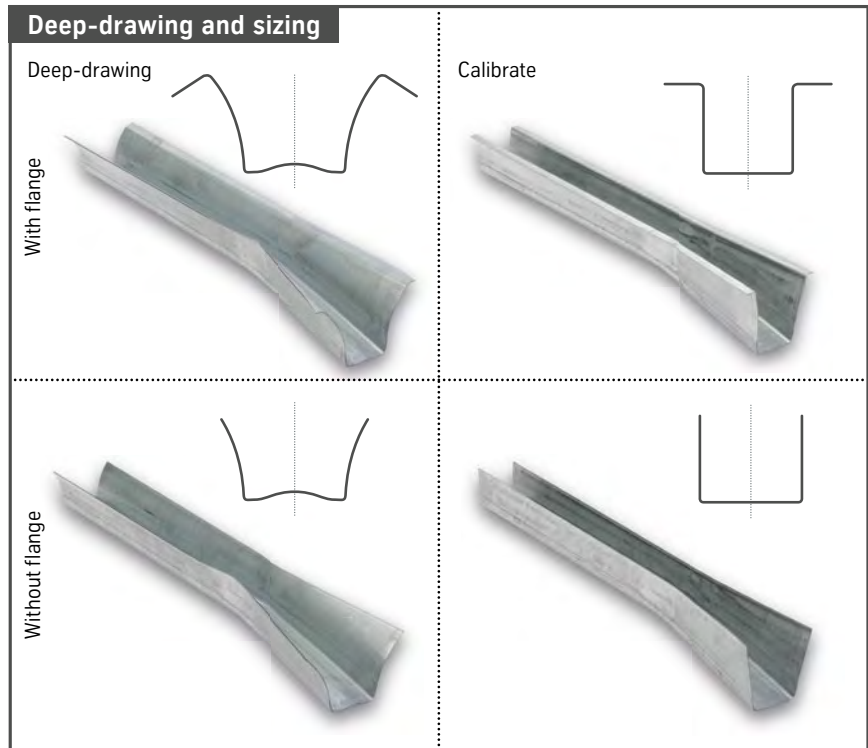
④ Structure of the drawing tool (left), pre-drawn U-shaped shell without welding flange (right)



⑤ Structure of the calibration tool (left), calibration of the U-shaped shell with welding flange (right)

face-end spacers and the lower part of the tool form the split calibration die. The punch is adapted to the relevant component variant using inserts. The punch is fitted with a calibration edge for the flange-free component; a shoulder is inserted for the component with flange, ⑤.

The punch and spacers initially move at the same time until the spacers are mechanically locked. The material is therefore locked all around on the tool side. Further on in the process, the calibration punch is moved to the lower dead center, whereby the extended flanges and ribs are longitudinally upset and the pre-shaped bottom is flattened. The previously inhomogeneous spring-back is transferred in the direction of the sheet plane, where it only exerts a minor influence on component dimensional accuracy, ⑥. Unavoidable trimming at the broad top end of the longitudinal member is only undertaken after this.



⑥ Form deviation compensation

PROCESS ADVANTAGES LEAD TO COST ADVANTAGES

High dimensional accuracy, the reduced use of material, the short process chain with simple tools and less trimming are significant advantages in comparison with conventional deep-drawing. The two connections for the subframe can also be integrated into the U-shaped shell, where they are easily accessible. The steel multi-section profile therefore combines the advantages of a shell solution with the lightweight-optimized profile design.

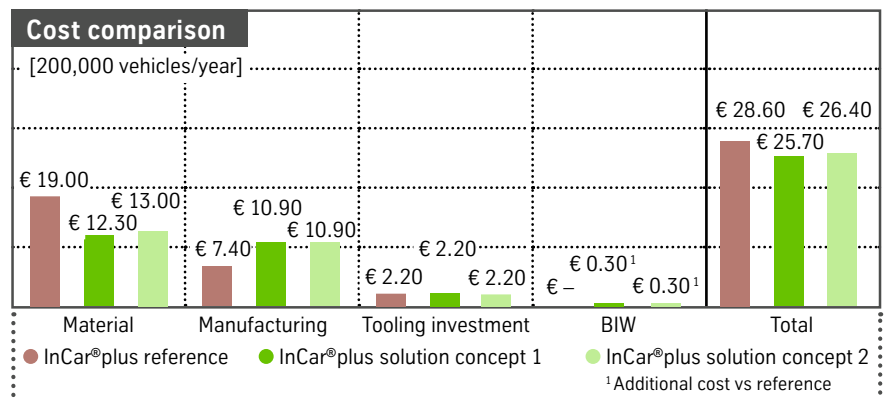
The longitudinal member is integrated into the body-in-white as a completed subassembly. After joining the T³ profile and the U-shaped shell, conventional processes are used to join components such as the impact plate, absorber, the suspension strut dome subassembly, the front longitudinal member bottom and the firewall crossmember. This assembly is then integrated into the body-in-white in one piece.

The cost comparison is based on the volume and manufacturing scenario used universally throughout InCar plus, ⑦. Due to the lower sheet thicknesses and the use of configured blanks (less offcut), the material costs for material variant 1 are 35 % lower in comparison with the two L-shaped shells used in the reference. As the axial forces in the AZT

load case are also borne by the center bridge and are therefore distributed better over the cross-section, the use of inexpensive monolithic blanks is possible. Tailored Blanks, as are used in the reference, are no longer necessary. In total, this leads to a cost advantage of 10 % with a simultaneous weight reduction of 3.5 kg per vehicle in comparison with the reference solution.

The selection of materials and sheet thicknesses specifically tailored to lightweight design and top crash perfor-

mance are not mutually exclusive in the multi-section design. While the T³ profile consists of CP-K 570Y780T with a thickness of 1.2 mm and the U-shaped shell consists of DP-K 700Y980T with a thickness of 1.4 mm (material variant 2), intrusion in the Euro NCAP and small overlap rigid barrier tests and plastic expansion in the AZT test lie within an acceptable framework. In comparison with the main concept, these materials simultaneously lead to an additional weight reduction of 1.2 kg per vehicle.



⑦ Cost comparison of the reference and InCar plus longitudinal members

SLIM A-PILLAR: BETTER VISIBILITY, LESS WEIGHT

The new InCar plus A-pillar offers numerous advantages in comparison with conventional A-pillars: a significantly larger field of vision, high passive crash safety and around 10 % less weight. Use of less material and innovative manufacturing technologies enable increased efficiency at very moderate lightweight design costs of € 1.57/kg. Cost advantages arise on integration of the A-pillar concept into a cross-model common parts strategy.

High structural mechanical requirements and the vehicle design are causing the A-pillars of current vehicle generations to become significantly wider. As a result of this, larger areas of the field of vision are being obstructed, leading to an increased risk of not seeing other road users or not seeing them in time, ❶. The vastly reduced cross-section of the A-pillar developed as part of the InCar plus project enlarges the free field of vision and therefore makes a significant contribution to accident prevention.

Together with the resulting increase in driving comfort, this creates an additional customer benefit which may positively affect the purchase decision.

Lower weight is a second, by no means less important, objective.

However, optimizing the field of vision and reducing weight conflict with the requirements of crash safety. In addition, the complex geometry of typical A-pillars makes high demands on the materials and manufacturing processes which are used. A multi-part shell design, which meets all current, crucial structural mechanical requirements and therefore represents the state of the art in 2014, serves as the reference for assessing the new A-pillar concept, ❷.

Within InCar plus, the objectives are achieved with a hot-formed, closed profile with integrated window flange which

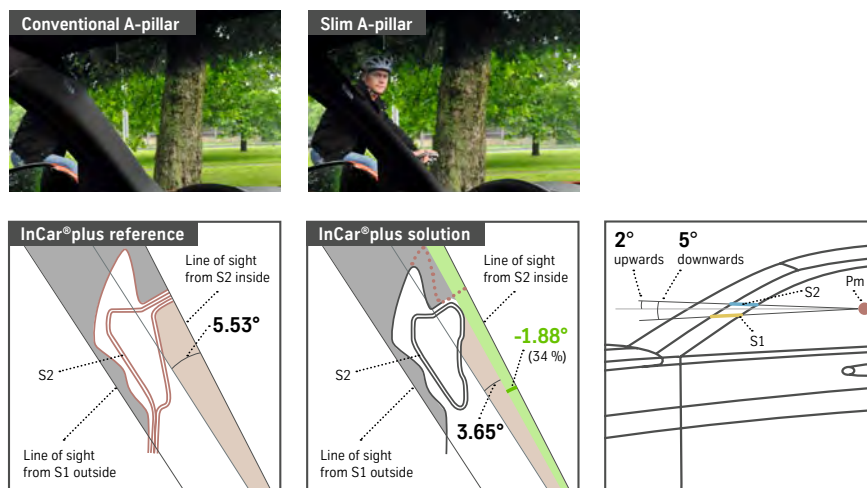
optimally exploits the reference's available package, ❸. This new A-pillar concept reduces the obstruction angle by a significant 34 % and the weight by 10 % or 3.22 kg per vehicle.

Structural mechanical validation of the A-pillar is based on the specifications of the Euro NCAP, Euro NCAP pole and IIHS small overlap tests as well as the FMVSS 216a roof intrusion test. On the whole, the A-pillar attains the target values of the relevant crash load cases and offers crash behavior comparable with that of the reference structure. The same

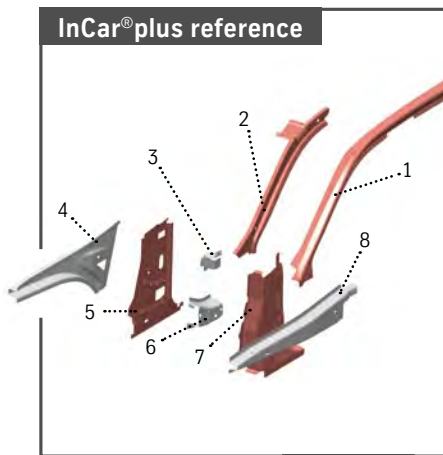
applies to the torsional and bending stiffnesses which are achieved. In combination with an optimal restraint system design, the risk of injury can be reduced to such an extent that the prerequisites for scoring five stars in the Euro NCAP test are created.

NEW PROCESSES OPTIMIZE MANUFACTURING

The investigation is focused on implementation of the complex A-pillar geometry in manufacturing. The component

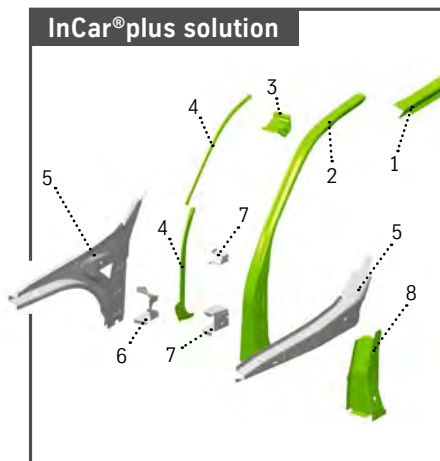


❶ Reduction of the obstruction angle



② Reference A-pillar components

No.	Part	Material	Coating	Thickness	Weight
1	A-pillar upper outer left	CP-W® 660Y760T	GI40	1.80 mm	4.40 kg
2	A-pillar upper inner left	MBW® 1500	AS150	1.15 mm	1.29 kg
3	Bracket cockpit beam left	CR300LA	GI40	1.50 mm	0.25 kg
4	Longitudinal member upper inner left	DP-K® 440Y780T	GI40	1.10 mm	2.07 kg
5	A-pillar lower inner left	RA-K® 400Y690T	GI40	1.10 mm	1.79 kg
6	Reinforcement A-pillar lower left	CR210IF	GI40	1.20 mm	0.64 kg
7	A-pillar lower outer left	MBW® 1500	AS150	1.20 mm	2.53 kg
8	Longitudinal member upper outer left	DP-K® 440Y780T	GI40	1.10 mm	2.04 kg
Total weight per vehicle					30.02 kg



③ InCar plus A-pillar components

No.	Part	Material	Coating	Thickness	Weight
1	Roof frame side outer left	DP-K® 590Y980T	GI40	1.30 mm	1.00 kg
2	A-pillar profile left	MBW® 1500	AS150/U	1.25 mm	4.95 kg
3	Bracket roof cross member front left	CR240LA	GI40	1.15 mm	0.20 kg
4	Flange support upper/lower left	CR240LA	GI40	0.90 mm	0.36 kg
5	Longitudinal member upper inner/outer left	DP-K® 440Y780T	GI40	1.10 mm	5.08 kg
6	Bulkhead A-pillar lower	DP-K® 590Y980T	GI40	1.20 mm	0.31 kg
7	Reinforcement A-pillar upper/lower left	CR380LA	GI40	1.20 mm	0.50 kg
8	A-pillar lower outer	DP-K® 590Y980T	GI40	1.20 mm	1.01 kg
Total weight per vehicle					26.82 kg

starts at the sill, proceeds along the hinge pillar, the windshield inclination, over the roof frame area and ends at the B-pillar connection. The ultra high-strength steel profile reveals all of the reference design's connection surfaces and follows the three-dimensional structure specified by the package.

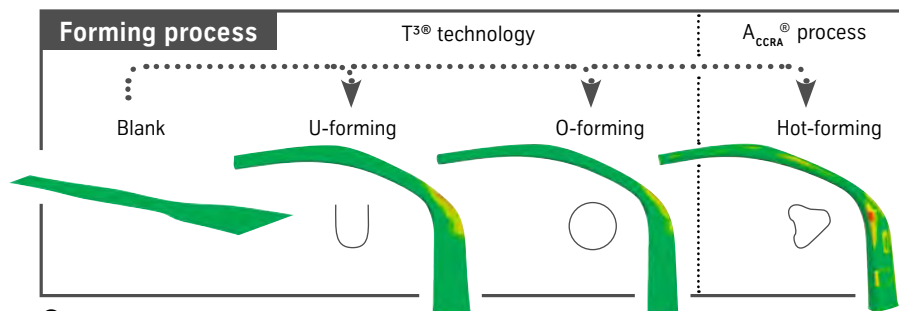
Necessary reinforcements are integrated into the closed profile with conventional body-in-white (BIW) methods.

Two forming techniques which supplement each other are used for manufacturing, ④. The T³ technology is a production process for manufacturing thin-walled, closed or open profiles with a flexible

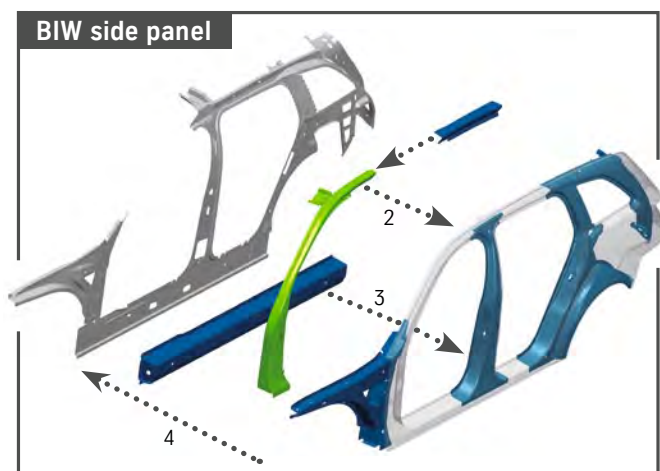
cross-section. First, the T³ technology is used to produce a curved, tubular semi-finished product with varying cross-sections. This semi-finished product obtains its final geometry in a further hot-forming operation, the Accra process developed by Linde + Wiemann.

In the InCar plus project, the engineers have additionally developed an industrialization concept which enables the closed profiles to be manufactured under conventional production conditions and with standard cycle times. The A-pillar semi-finished product can be manufactured either on an individual press or conventional pressing lines. High material exploitation is achieved through the use of the blanks and optimal nesting.

Accra is an innovative manufacturing process for crash-optimized, ultra high-strength structural components consisting of closed hollow profiles (form blow



④ Overall T³ and Accra process chain



5 Integration of the InCar plus A-pillar into the outer/inner side panel (left) with important joining parameters (right)

Scope of joints side panel/ vehicle	InCar®plus reference	InCar®plus solution	Difference
No. of spot welds	1,325	1,293	-32
MIG/MAG welding	700 mm	3,856 mm	+3,156 mm
Laser beam welding	0 mm	1,440 mm	+1,440 mm
Structural adhesive	31,470 mm	28,702 mm	-2,768 mm

hardening) and combines the advantages of hydroforming and press hardening. In the Accra process, the semi-finished profiles manufactured using the T³ technology are heated to the austenitization temperature (880 to 950 °C) in a furnace and inserted fully automatically into a hot-forming tool. When the tool is closed, the semi-finished product is molded into the three-dimensional shear line. Sealing elements seal the semi-finished product at the ends on both sides. The final component contour is then formed by means of internal high pressure (with compressed air in the simplest case) of up to 600 bar. After forming, the internal pressure is reduced and water flows through the component through the sealing elements. Depending on the material thickness, direct cooling leads to an

extremely rapid and even cooling rate of up to 350 K/s. This guarantees process-consistent and reproducible phase transformation from austenite to martensite. The structure and therefore also the characteristics of the finished component are comparable with those of conventionally press-hardened shell components. After hot-forming, lasers trim the ends of the component and cut holes and cutouts. No springback is usually to be anticipated. The finished component's dimensional tolerances lie in the range of +/- 0.5 mm.

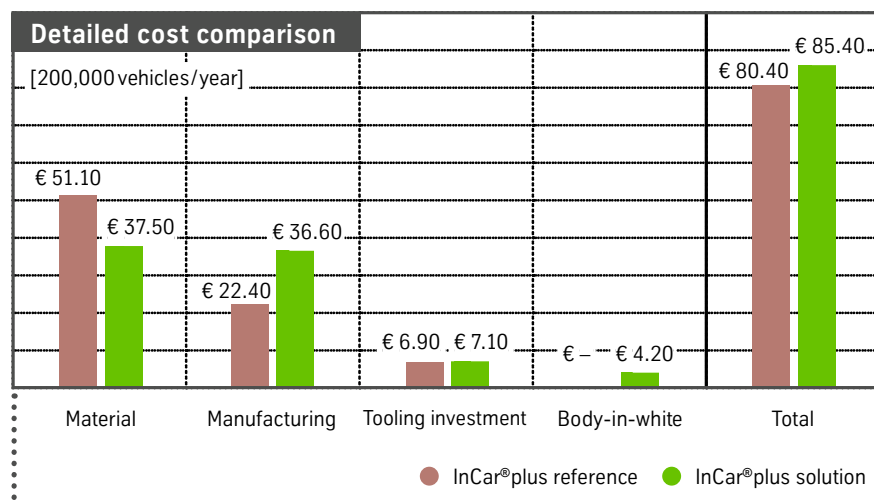
The combination of these two innovative manufacturing technologies enables extremely complex component geometries to be achieved which could not previously be manufactured with the familiar manufacturing techniques and comparable material strengths.

In interaction with the technical characteristics of hot-formed hollow profiles manufactured from MBW 1500, both techniques make a significant contribution towards optimizing the weight of structural components. The components manufactured in this way can usually be integrated into existing body-in-white systems with ease, e.g. through modified joining sequences and adapted joining techniques. 5 shows an example of the joining sequence for the outer/inner side panel.

The concluding cost assessment gives consideration to the adapted body-in-white scopes. Attractive lightweight design costs of € 1.57/kg with a weight reduction of approximately 3.2 kg per vehicle arise in combination with the reduced use of material, 6.

COMMON PARTS STRATEGY POSSIBLE WITH SEMI-FINISHED AND FINISHED COMPONENT

The hot-formed A-pillar profile offers an additional advantage: it can be specifically adapted as required by the customer, e.g. with regard to a vehicle-based geometric modification. This means both that the length of the A-pillar can be varied and that the profile can be transferred to other models as part of a common parts strategy. The common parts strategy does not therefore merely refer to the use of the same semi-finished product. This may be a technically and economically interesting option for the final, formative manufacturing process. The manufacturing processes can also be transferred to other body, chassis or steering components.



6 Comparison of the InCar plus reference and InCar plus solution lightweight design costs

WEIGHT REDUCTION THANKS TO HOT- AND COLD-FORMED B-PILLARS

Tribond 1400, the roll-clad steel composite material developed for hot-forming, enables a weight reduction of 1.28 kg per vehicle in comparison with a Tailored Tempering B-pillar made of MBW 1500. The lightweight design costs are just € 1.47/kg. New steel materials such as DP-K 700Y980T, which offer weight reduction potential and cost advantages, are also available for cold-forming.

The B-pillars are central components in a vehicle's safety passenger cell, ❶. Particularly in a side crash, they must be able to withstand extremely high stresses to offer passengers the necessary survival space. As part of InCar plus, ThyssenKrupp is developing new B-pillar outer parts using a range of innovative steel products which obtain their final geometry through either hot-forming or cold-forming, ❷. The technical solutions described in the following meet the same high structural mechanical requirements as the reference structure.

The investigations are focused on manufacturing analysis and implementation of the real B-pillar outer parts. In addition to these B-pillar outer parts, a B-pillar reinforcement made of MBW 1500 and adapted to their structural mechanical performance is also analyzed for the weight and cost assessments. The B-pillar inner parts, the roof

frame, sill and seat crossmember in all variants are identical to the reference.

Tribond 1400, which is currently still in development, offers the most advantageous characteristic combination of any hot-formed material. The material will be available with an aluminum-silicon coating. Tribond 1400 offers significantly better bending characteristics than MBW 1500. Among other aspects, this leads to improved energy absorption behavior without material failure in the event of a crash. Cold-forming alternatives include the high-strength, cold-rolled multiphase steels DP-K 700Y980T (standard) and DP-K 780YT1180T (in development). They can be implemented both as Tailored Blank solutions and, with slight geometric limitations, as monolithic B-pillar outer parts. Despite the further increase in strength to at least 1180 MPa, DP-K 780Y1180T, as a forming-optimized dual-phase steel in the 1200 MPa

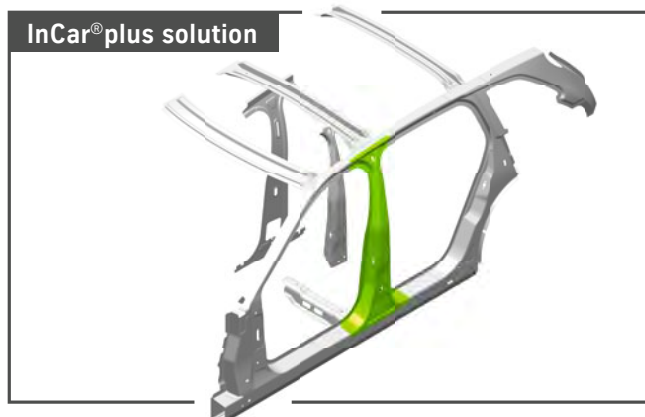
strength class, reveals virtually the same potential as the steel in the lower strength class in terms of geometrically possible component complexity.

STRUCTURAL MECHANICAL VALIDATION

All solutions are coordinated to the IIHS side crash load case. In the individual solutions, buckling resistance in the upper area is ensured by a press hardened MBW 1500 reinforcement adapted to the material thickness. In addition, the material thickness determines the ductility of the steel used for manufacturing the technically complex base area of the B-pillar outer parts. ❸ shows an example of the evaluation of the IIHS test for the solution consisting of the new, cold-formed multiphase steel DP-K 700Y980T with a material thickness of 1.70 mm. Structural deformation lies within the green area of the assessment template. Occupant protection is therefore guaranteed.

FORMING SUITABILITY AND JOINING TECHNOLOGY VERIFIED

The reference and all alternative variants were fundamentally investigated as regards their manufacturing suitability for hot-forming or cold-forming and joining. Due to the high strength level of the reference solution, significantly thinner sheets are not to be anticipated in the cold-formed solutions as they have to meet the same structural mechanical design criteria. In addition, the geomet-



❶ Outer B-pillar in the body side frame

Concept	Upper area		Lower area (foot)		Reinforcement		Weight
Reference	MBW® 1500 1.70 mm Tailored Tempering				MBW® 1500	2.10 mm	15.42 kg
Hot-forming							
Concept 1	MBW® 1900 1.50 mm Tailored Tempering				MBW® 1500	2.10 mm	14.22 kg
Concept 2	TriBond® 1400 1.30 mm				MBW® 1500	2.55 mm	14.14 kg
Cold-forming: B-pillar outer in tailored blank design							
Concept 3	DP-K® 700Y980T	1.70 mm	DP-K® 330Y590T	1.80 mm	MBW® 1500	2.10 mm	15.70 kg
Concept 4	DP-K® 700Y980T	1.70 mm	TPN®-W 660Y760T	1.70 mm	MBW® 1500	2.10 mm	15.42 kg
Concept 5	DP-K® 700Y980T	1.70 mm	TPN®-W 700Y870T	1.60 mm	MBW® 1500	2.10 mm	15.14 kg
Concept 6	DP-K® 780Y1180T	1.60 mm	TPN®-W 700Y870T	1.60 mm	MBW® 1500	2.10 mm	14.82 kg
Cold-forming: B-pillar outer in monolithic design							
Concept 7	DP-K® 700Y980T 1.70 mm				MBW® 1500	2.10 mm	15.42 kg
Concept 8	DP-K® 780Y1180T 1.60 mm				MBW® 1500	2.10 mm	14.82 kg

2 Table of investigated steel grades and forming processes

ric complexity of the B-pillar outer parts limits forming to a certain extent, but in turn offers active corrosion protection.

Geometric adaptations, e.g. of the transitional radii, are necessary due to

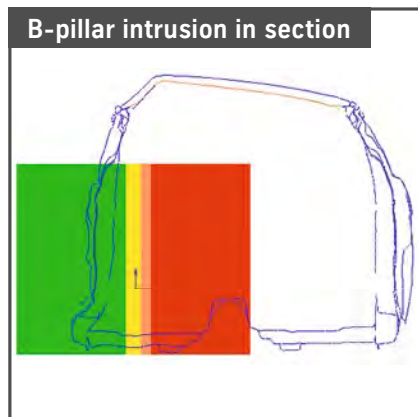
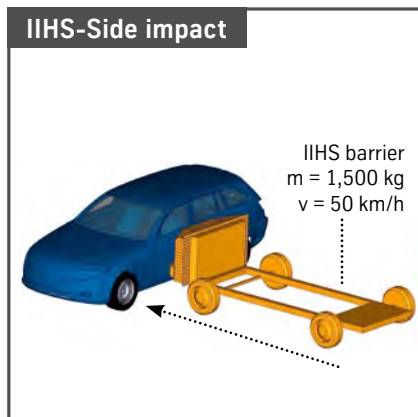
the high strengths in combination with cold-forming. Despite these challenges, success has been achieved in manufacturing complex components such as the B-pillar outer parts with the selected

materials. One significant advantage of all cold-formed steels is their availability with zinc surface coating. This offers sufficient cathodic corrosion protection for the corresponding structures even without special measures. The steels for hot-forming and the new, cold-forming, high-strength steels have also been investigated as regards their welding suitability. Sufficiently large process windows exist, especially for resistance spot welding.

COMPONENT TESTS CONFIRM MATERIAL SUITABILITY

To validate the virtual results, all B-pillar outer parts on the assemblies are subjected to dynamic three-point bending tests, 4. The lower area of the B-pillar assembly is subjected to defined stress in the drop tower test by the solid ram which impacts at 30 km/h. As a result, the energy effect is identical for all solutions and the energy absorption statements are therefore comparable. A high-speed camera with a frame rate of 1000 Hz documents the tests.

The test for the Tribond 1400 composite reveals reproducibly high force absorption at the point of maximum force and over the entire deformation path, 5. The energy absorption of the completely press hardened Tribond 1400 corresponds to the reference solution consisting of MBW 1500 in the Tailored Tempering process (see article "Tailored Hot-forming" from page 105). The materials of the two specimens are each 1.70 mm thick. The recognizably smaller



3 Simulation of the IIHS test for the DP-K 700Y980T B-pillar with a thickness of 1.70 mm



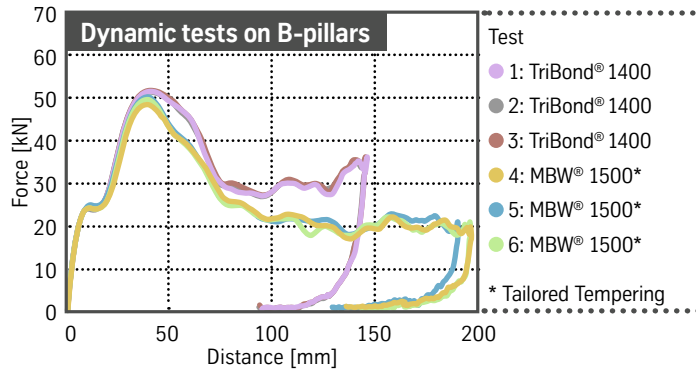
4 Dynamic three-point bending test setup (left), Tribond 1400 without failure (right)

deformation for the Tribond 1400 specimens enables the material thickness to be reduced to 1.30 mm. No critical incipient failure cracks can be observed in the material. This practical component test additionally enables the innovative Tribond 1400 steel composite material to be validated for B-pillar outer parts which are subject to extensive stress in a crash.

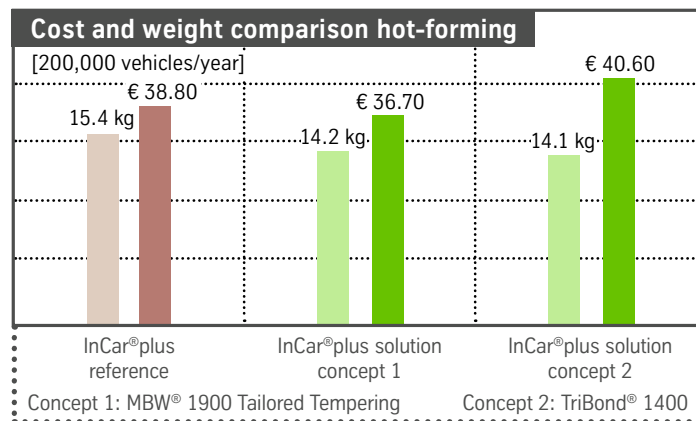
EXTENDED RANGE OF SUITABLE, INEXPENSIVE STEELS

The cost and weight comparison of all InCarplus variants against the reference is shown in 6 and 7. The lightest variant is the Tribond 1400 B-pillar (with a weight reduction of 1.28 kg). The B-pillar solution with the MBW 1900 steel processed in the Tailored Tempering process (thickness 1.50 mm) also offers a significant weight reduction of 1.2 kg per vehicle with a cost advantage of around 5 %.

Alternatives include B-pillar outer parts consisting of hot- or cold-rolled multiphase steels which are cold-formed. Depending on geometric complexity, both Tailored Blank solutions and, to a lesser extent, even monolithic B-pillar outer parts can be achieved. The monolithic solutions offer slight cost advantages, e.g. DP-K 700Y980T up to 4 %. Conversely, variants consisting of Tailored Blanks offer the option of optimally combining the individual steel sheets in terms of the desired functional-

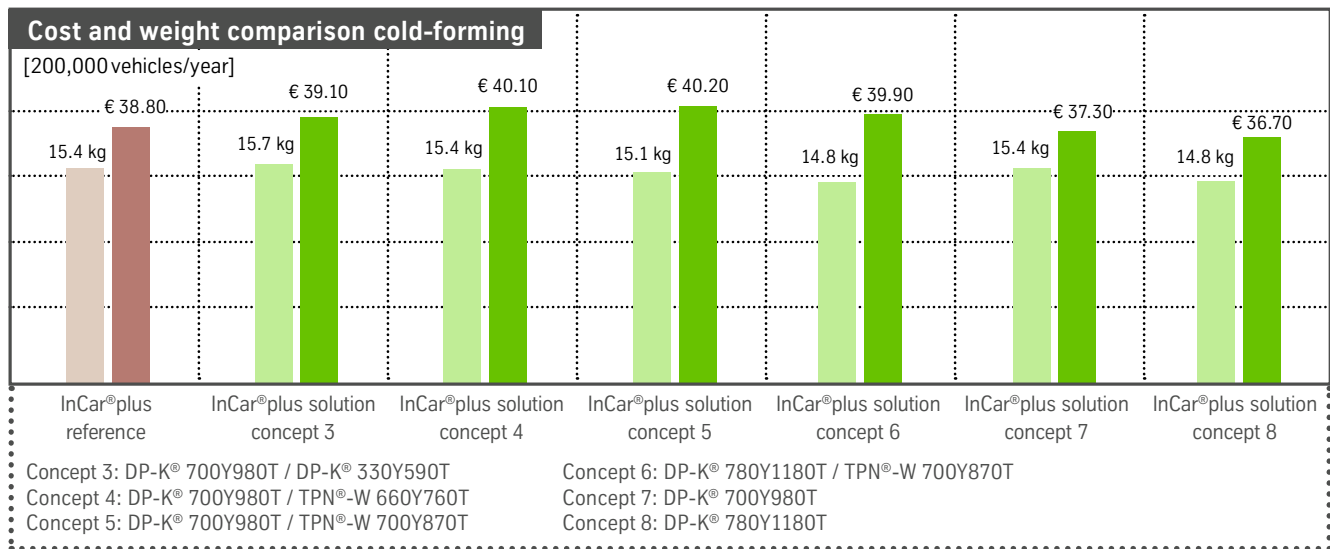


5 Force-distance curve of Tribond 1400 and MBW 1500 reference in the dynamic three-point bending test



6 Cost and weight comparison of all solutions with hot-formed materials

ity. The lightest Tailored Blank combination enables a weight reduction of 0.6 kg with a slight cost disadvantage of less than 3 %. An extended range of suitable steels is therefore available for the specific technical and economic requirements.



7 Cost and weight comparison of all solutions with cold-formed materials

TAILORED HOT-FORMING

ThyssenKrupp has supplemented hot-forming with the Tailored Tempering process, which enables process-consistent manufacturing of components with tailored and locally differing mechanical properties. The specific, internal know-how also includes a detailed, virtual process and structure description for the hot-formed components. A prototyping tool for the B-pillar with precise temperature control and in-line measurement technology enables validation.

The hot-formed B-pillar variants reference (with MBW 1500) and variant 1 (with MBW 1900) described in the article “Weight Reduction thanks to Hot- and Cold-formed B-pillars” (see from page 102) were produced in the Tailored Tempering process. In the following, tool development and method planning in the application of this process will be examined in greater detail.

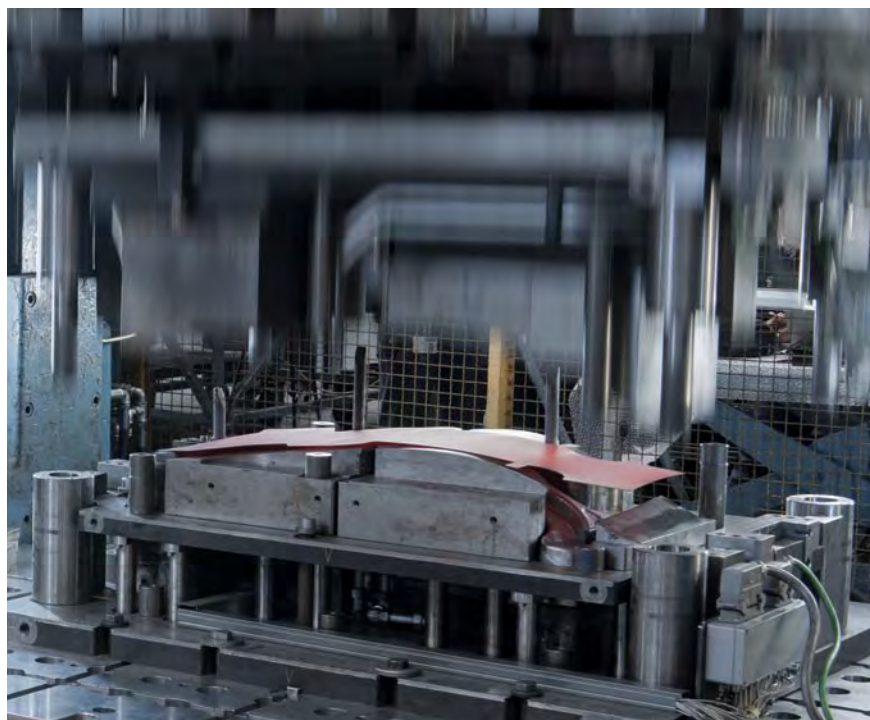
To achieve optimized crash performance, the base area of a B-pillar, i.e. from roughly below the door latch down to the sill, should be of a particularly energy-absorbent design to be able to transform as much impact energy as possible into deformation in case of a crash. Conversely, the upper B-pillar area must reveal high deformation resistance to prevent intrusion. This specification can be implemented very precisely using the Tailored Tempering process, ❶.

In the Tailored Tempering process, the cooling speeds in the material and thus structural changes are controlled by means of partially heated tool elements. The formation of locally varying structure types is therefore possible. For example, geometrically limited martensitic, ferritic-pearlitic or ferritic-bainitic structures can be achieved. This enables the achievement of requirement-based mechanical properties in the material or component. In contrast, a constant cool-

ing rate over the entire component surface is desired in the conventional hot-forming process in order to attain the formation of a martensitic structure throughout the component.

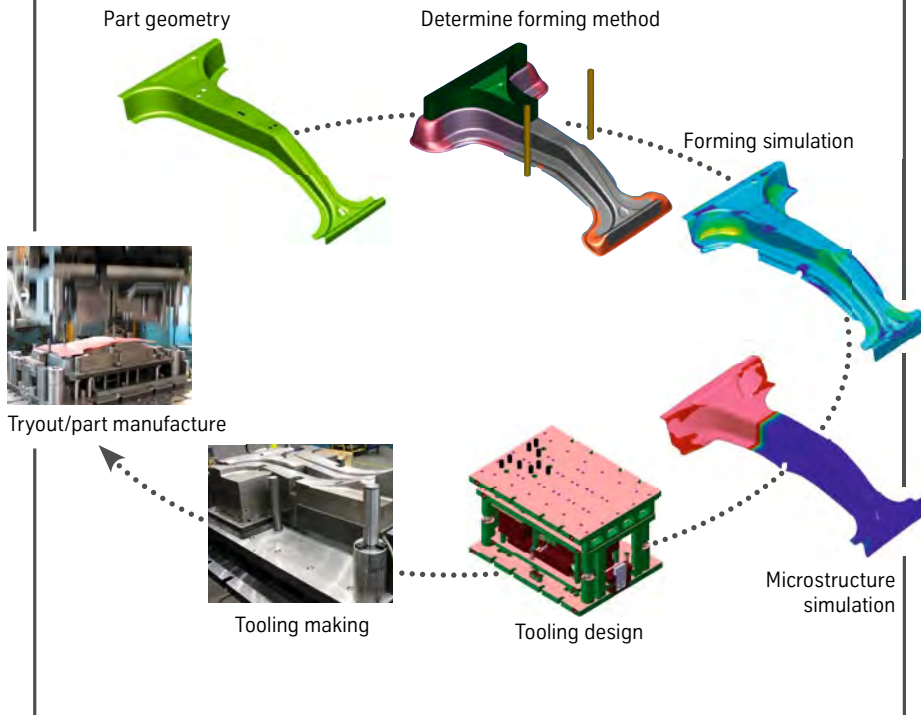
The process necessitates the most homogeneous temperature possible at

the active surfaces of the tool. Further requirements specified for the hot-forming tool developed as part of the project are regulated temperature management of the active tool elements up to 550 °C, process control during forming by means of pyrometer sensor technology inte-



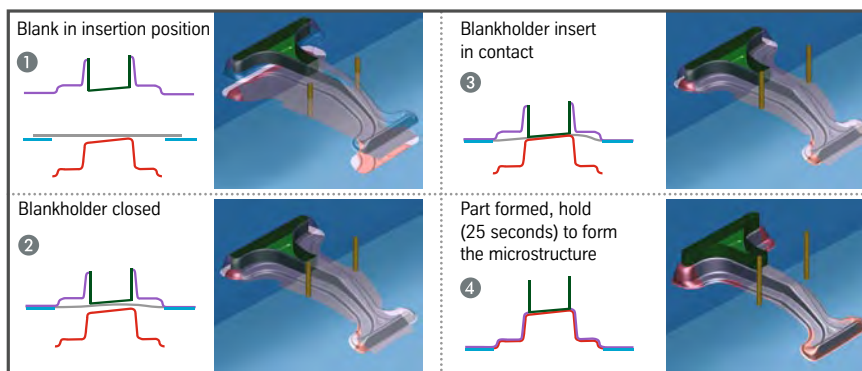
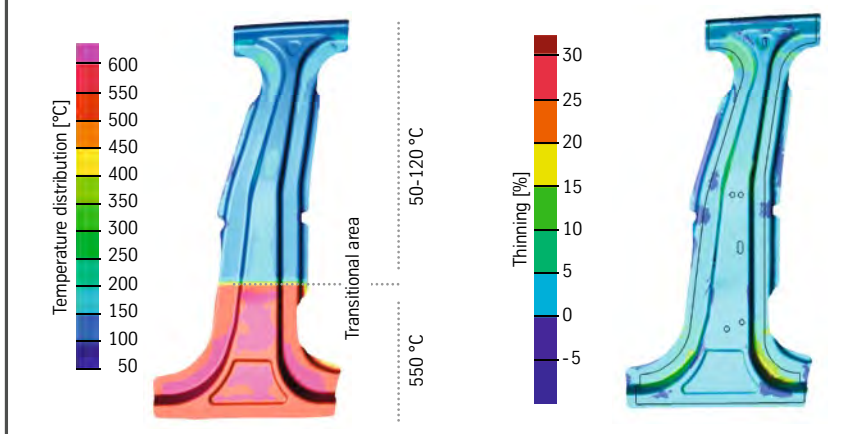
❶ Press stroke: Tailored Tempering tool with inserted blank

Manufacturing expertise at ThyssenKrupp



② Development steps from component geometry to near-production pressing

Development of forming method



③ Technical forming process development simulation results and tool kinematics

grated into the tool as well as temperature- and wear-resistant tool steel. Added to this is a modular tool design for full hardening and Tailored Tempering.

The hot-forming tool development process consists of several phases, ② and ③. Attention is initially focused on validation of the forming method and verification of component manufacturing feasibility. This is undertaken using standard FEM software solutions with which the forming process is simulated in detail.

Several loops, in which the component geometry and forming process are successively developed, are run through during the course of development until process-consistent B-pillar manufacturing has been verified through simulation.

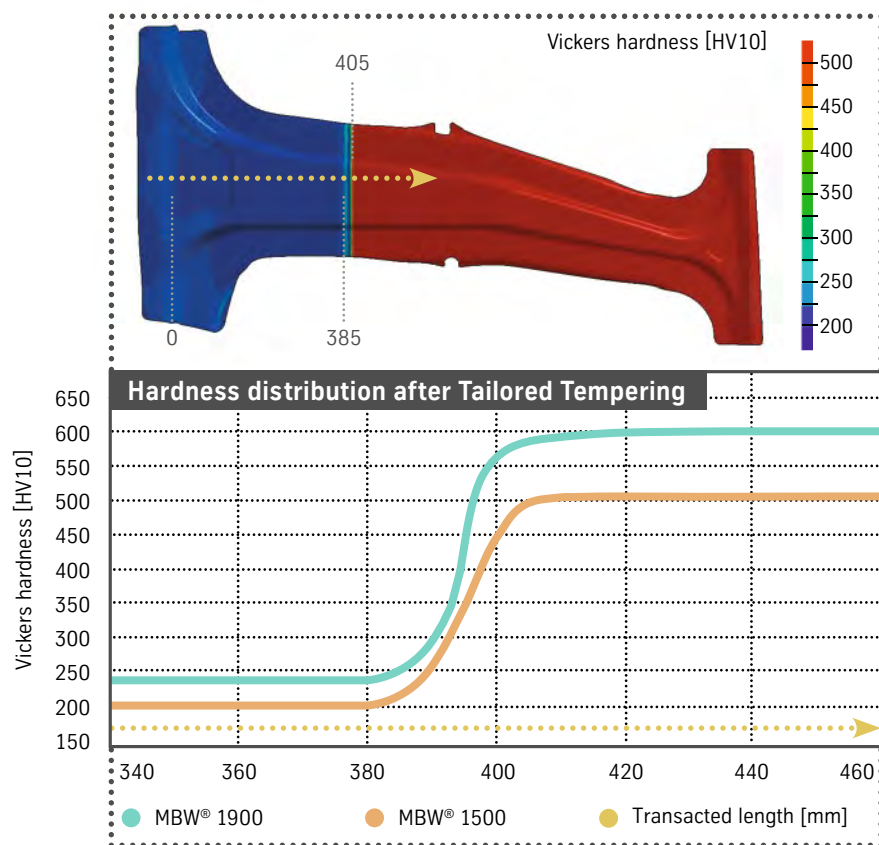
In a second simulation phase, the forming method developed under these aspects is then further optimized as regards prediction of the final component properties (structure simulation), ③. This forms the basis for creating the complex hot-forming tool.

The initial design draft is used as the basis for specific thermal heating system simulations. In this phase, the active elements are equipped with heating elements and combined to form optimally effective heating circuits. The required heat output is also determined, taking corresponding reserves into consideration. To further extend knowledge of handling the tools, which can reach temperatures as high as 600 °C, a second, compact test tool is constructed to accompany the activities for the B-pillar production tool.

This “thermal simulation calibration tool” extensively represents the geometric and physical characteristics of the B-pillar tool.

It therefore enables validation of the thermal simulation and the establishment of know-how in handling high-temperature tools. Even heating of the temperature-resistant tool material is investigated and optimized there in several iteration stages. Further unknown factors such as the compensation of thermal expansion and thermal insulation from neighboring tool components are also investigated on this tool.

The information thus acquired is used to further optimize the heat output and homogeneity of the active surface temperature by adjusting the positions of the heating cartridges in the main tool.



4 Hardness distribution with a sheet metal thickness of 1.70 mm after the Tailored Tempering process for MBW 1900 and MBW 1500

These corrections are integrated into the design measures for compensating for the thermal expansion behavior on the main tool.

Completion of the tool is followed by tryout, in which the originally defined requirements are successfully tested. The sensor technology installed in the tool can be used to track and record the blank's temperature curve during forming. These measurement data are used firstly to draw conclusions regarding the hardness and quality of the component, and secondly to implement further optimizations in the forming simulation in terms of the description of the physical heat transfer between the blank and tool.

VIRTUAL STRUCTURE PREDICTION IS SPECIFIC KNOW-HOW

One significant aspect of process design is prediction of the required characteristics. If the structure attained in the steel is known, statements on the anticipated hardness, local strength and ductility characteristics can be made.

To do this, it is first necessary to determine the process parameters suitable for the relevant material and its thickness, such as tool temperature, cooling rates, press forces and contact time. These parameters ultimately ensure that the component reveals the desired characteristics after the Tailored Tempering process. A relatively narrow transitional area between the press hardened and tempered area is also desired in the investigated variants of the B-pillar outer part. However, the technology basically enables transitional areas of different widths. This can be implemented by separately controlling the heating elements in the transitional zone using a separate heater circuit.

The process window for this manufacturing process is very robust at tool temperatures of 550 °C which are present here. The hardness distribution in the component for the MBW 1500 and MBW 1900 steels is determined using a virtual, advanced design, 4. A hardness of 480 to 500 HV (MBW 1500 curve) in the press hardened upper area corresponds to a strength of around 1500 MPa. In the

tempered B-pillar base, a hardness of around 200 HV corresponds to the desired strength of approximately 650 MPa. With the selected material thickness of 1.70 mm, the transitional area is only around 20 mm.

Under comparable process conditions, higher strength values are attainable for the MBW 1900 material in both the upper, through-hardened area and the tempered base of the component.

This higher strength basically enables the material thickness to be reduced while retaining the assembly's functionality. In this case, the B-pillar outer parts, the implemented thickness is 0.20 mm less than that of the reference solution.

The option of virtually predicting structure contents in the steel after the Tailored Tempering process and therefore optimally designing the component characteristics in early development phases significantly extends the range of applications possible for the established hot-forming steels MBW 1500 and MBW 1900. Development work for MBW 1900 steel is in the final phase.

APPLICATION POTENTIAL OF LITECOR IN THE BODY

In addition to outer panel components, ThyssenKrupp has also manufactured structurally-relevant inner parts using the Litecor steel-polymer composite in a potential analysis. Technical component forming feasibility is checked in simulations; the joining technology boundary conditions for the individual components are also scrutinized. The body's technical performance is analyzed in stiffness, NVH and crash simulations. In this study, the body reveals potential for the application of 14 Litecor parts. With the same performance, these are a total of 19.1 kg or around 20 % lighter than conventional components.

The declared objective of developing the Litecor composite product is cost-attractive lightweight design for large shell components – both for inner parts and in outer panel quality. Litecor is a three-layer composite which combines the high strength of steel with the low density of plastic and is also suitable for cataphoretic painting, ❶. It consists of an upper and lower steel cover

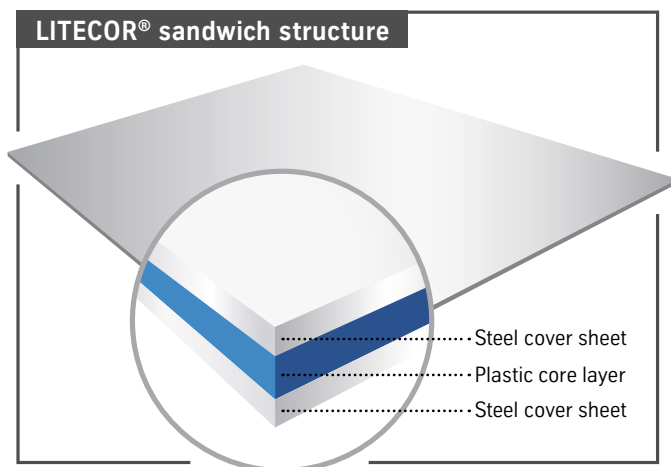
sheet, each with a thickness of 0.20 to 0.25 mm, which is attached to a plastic core layer by an adhesive of between 0.30 and approximately 1.0 mm to form a sandwich material. The thermoplastic compound layer with variable thickness acts as a firm spacer, with the result that even a slight increase in the core thickness results in a disproportionately high increase in bending and

buckling stiffness. Virtually no added weight occurs due to the polymer's low density of 1.03 g/cm³. The weight reduction in comparison with steel blanks with the same bending stiffness is up to 40 %.

Besides its weight and stiffness advantage, Litecor is also suitable for implementing typical steel design features such as striking styling edges in forming. At the same time, the lightweight design costs are lower than those of alloy components.

To meet the technical forming requirements, certain of which are more demanding, an IF steel grade which can be easily formed is used. Its strength is higher than that of soft deep-drawing steels. The dent resistance required e.g. in the event of hail impact or minor car park bumps is therefore ensured. The cover sheets are electrogalvanized on both sides to meet automotive corrosion requirements.

For use as structural components, higher strength steel grades are recommended as material for the cover sheets. In a crash, these offer energy-transforming properties with structural stability of



❶ Litecor composite

the composite structures at the same time. Possible Litecor structural components include the firewall and floor panels, for example, ②.

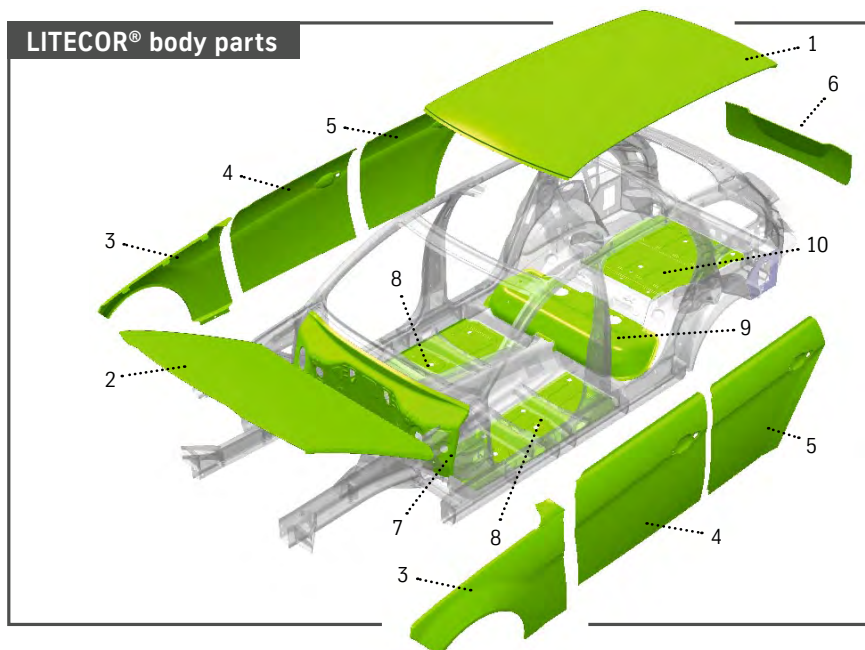
COMPREHENSIVE VIRTUAL ANALYSIS

This potential analysis encompasses a total of 14 Litecor parts with a sandwich structure which meets the requirements. On selection of the Litecor parts, the outer panels are taken into consideration due to their high weight potential and stiffness requirements. These components have an external steel cover sheet with a thickness of 0.25 mm and therefore meet the dent resistance requirements, e.g. in the event of hail impact. On the inner side, a 0.20-mm thick steel sheet is used for maximum weight saving. Inner parts with reduced crash relevance are also designed in Litecor to achieve further weight savings. The Litecor parts can be integrated into existing scenarios with minimum effort. Litecor's thermal expansion is similar to that of sheet steel, as is its recycling process.

The individual sandwich components are initially dimensioned through forming simulations. A forming simulation model which enables realistic predictions for the classic evaluation criterion of crack and crease formation is available for Litecor, ③. On the basis of shell and volumetric elements, the physical behavior of the sandwich material is plausibly simulated even for complex local forming processes such as hemming. Adaptations for trimming and grid refinement functions with volumetric elements have been created in cooperation with software developers to provide method planners with a practical tool for forming simulations.

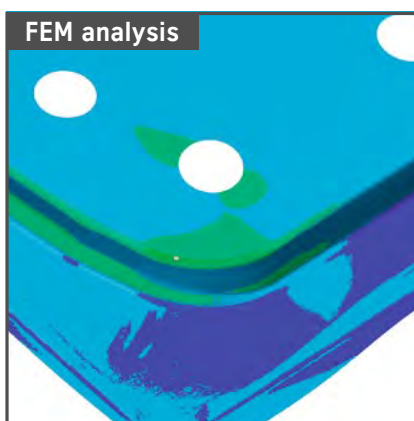
LITECOR WELL SUITED FOR JOINING

To be able to use Litecor effectively in body-in-white design, it is particularly necessary to employ resistance spot welding in combination with adhesive bonding. Due to its special material



No.	Part	Composite structure (thickness of individual layers in mm)
1	Roof outer panel	0.25 / 0.40 / 0.20
2	Hood outer panel	0.25 / 0.40 / 0.20
3	Fender front right/left	0.25 / 0.40 / 0.20
4	Front door outer panel right/left	0.25 / 0.40 / 0.20
5	Rear door outer panel right/left	0.25 / 0.40 / 0.20
6	Tailgate outer panel	0.25 / 0.40 / 0.20
7	Firewall	0.25 / 0.40 / 0.25
8	Main floor middle right/left	0.20 / 0.40 / 0.20
9	Floor panel rear seat	0.25 / 0.40 / 0.25
10	Floor rear	0.20 / 0.40 / 0.20

② Overview of Litecor body components and their layer structure



③ Comparison of the simulation (left) and component (right) in a critical forming location

structure, Litecor is only conditionally suitable for the thermal joining processes (resistance spot, laser beam and arc welding) used in vehicle design.

Cold mechanical joining processes such as punch riveting and bolting were therefore analyzed in an initial step. During generally suitable semi-tubular punch riveting, Litecor, as the underlying material, should not be the last element in the joint structure to be penetrated by the rivet. Using semi-tubular punch rivets in combination with adhesive bonding is generally recommended. In this case, adhesive bonding is subject to the same boundary conditions as those applicable to galvanized steel sheets.

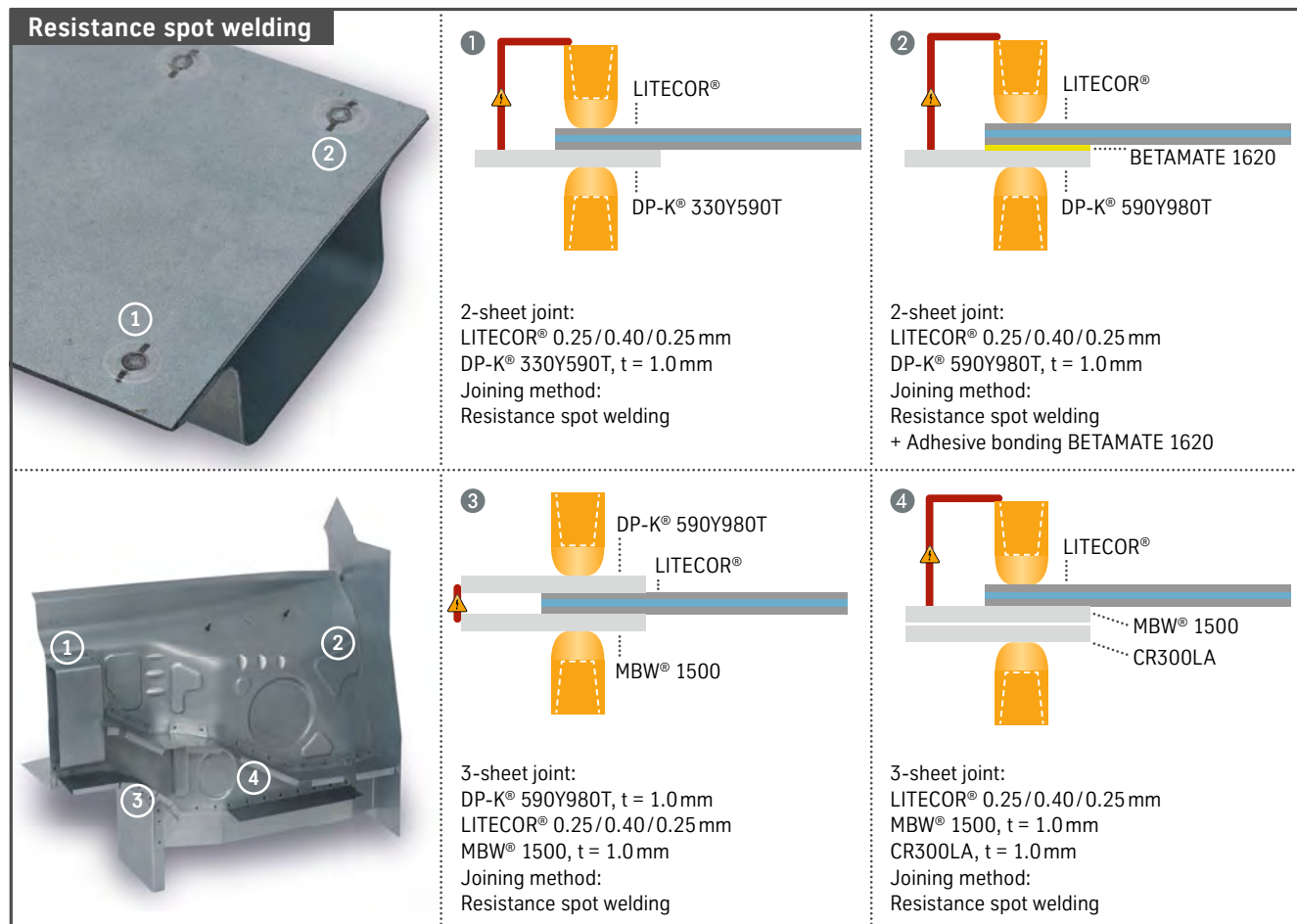
Under the influence of thermal stress, creeping effects may occur in the core layer in the case of mechanical joining elements with preload force, such as bolts. This effect can be countered by locally pre-conditioning the joining point, e.g. in the forming tool, prior to joining.

MIG, MAG and laser beam welding are not possible due to the material structure. Laser brazing at low temperatures can be used after adapting the process parameters and the auxiliary materials. Production process suitability must be verified in the individual case.

In the second step, a new resistance spot welding process was developed to qualify Litecor for this process and for combined spot welding and adhesive bonding. In a practical test program, Litecor revealed process consistency in resistance spot welding with different steel grades in both two- and three-sheet versions with only minor modifications to a standard welding system. The attained joint qualities and strength values meet the requirements, and the robustness of the process was confirmed. With a view to use in production, a prototype welding system is being developed at ThyssenKrupp to enable near-production testing and qualification of the pro-

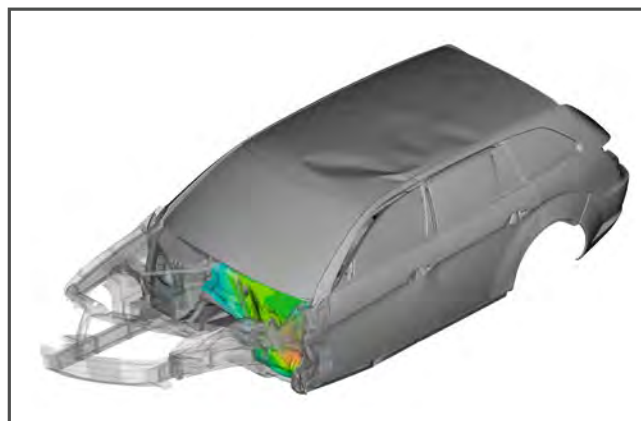
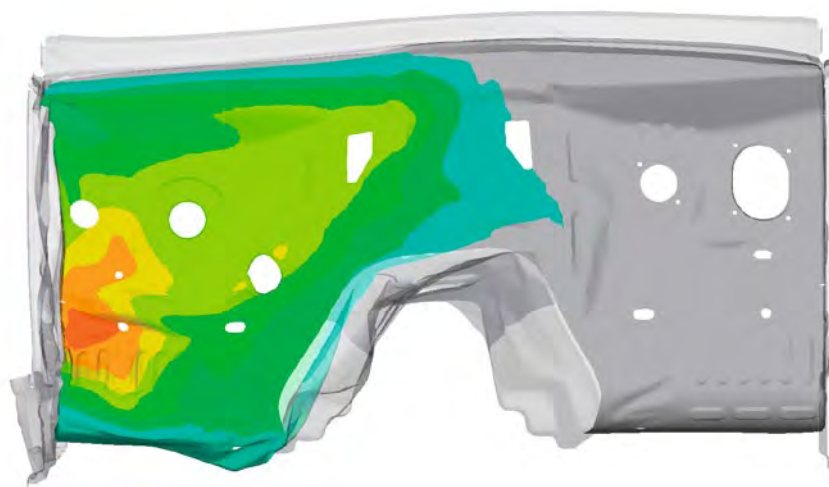
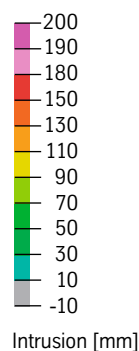
cess. The firewall serves as a demonstrator; resistance spot welding and adhesive bonding will be employed to join it to the surrounding steel body components such as the tunnel, A-pillar, firewall cross-member and reinforcement elements, 4.

For all outer panel components ThyssenKrupp recommends IF steel grades which meet requirements for oil canning and dent resistance. As for conventional solutions, the dent repair methods ("dent doctor") are available for permanent dents caused e.g. by hail impact or minor car park bumps. Steel cover sheets with a thickness of 0.25 mm or more are usually selected for structural components to meet the higher strength requirements. In two cases, higher strength steel grades are also used to increase the load level that can be withstood in a crash. According to current information, Litecor offers forming capability similar to that of monolithic sheets of the same basic grade.



4 Resistance spot welding of Litecor with typical material pairings in body design

Crash simulation



⑤ Litecor firewall intrusion after Euro NCAP frontal crash

SAFE AND LIGHT

Noise, vibration and harshness (NVH) simulations are also performed on the basis of the numerical stiffness model to determine natural frequencies and avoid critical vibration modes. As part of these simulations, moderate thickening is required for certain steel reinforcement parts in the body. As a result, support effects and local yields are optimized in the design. The resulting, additional weight of 2.6 kg is taken into consideration in the Litecor body's weight balance. At the same time, increased damping can be exploited to undertake specific minimization at the secondary acoustic materials, possibly resulting in a further weight and cost advantage with Litecor.

In parallel with the NVH and stiffness simulations, the body is tested and eval-

uated as regards five representative crash load cases (Euro NCAP Front, IIHS SORB, FMVSS 301, Euro NCAP Pole) in crash analyses. In this case, individual steel components are replaced with Litecor parts in iterative loops in the crash model and their technical performance is analyzed. Following adaptation of the layer thicknesses and, if necessary, the choice of the steel cover sheets' strength class, the final Litecor body variant meets all crash requirements in a manner similar to the reference body, ⑤. However, it is 19.1 kg lighter in comparison. Litecor is therefore outstandingly suitable for meeting further weight reduction requirements.

OUTLOOK

At present, ThyssenKrupp is working intensively to construct a manufacturing

system suitable for volume production of Litecor. Volume production of Litecor material for inner parts is initially planned in the medium term, with outer panel material to follow.

INNOVATIVE LIGHTWEIGHT DESIGN CONCEPTS FOR HOODS

Modern steel technologies and lightweight design concepts are making hoods over 20 % lighter. This lightweight design potential can be accessed by using the flexurally stiff and light steel-polymer composite Litecor without having to compromise on performance or safety. Low lightweight design costs additionally ensure that this solution is economically very attractive. A multi-material concept with magnesium sheet metal even enables a weight advantage of up to 40 %.

As part of InCar plus, ThyssenKrupp has studied various concepts for light and cost-optimized hoods, ❶. The Litecor steel-polymer composite, which offers optimized stiffness and consists of two

very thin steel cover sheets and a plastic core, is particularly suitable for meeting the partly contradictory requirements of stiffness and pedestrian protection. The thickness of the steel cover sheets and

the plastic core can be varied, thus enabling tailored solutions for special applications and requirements.

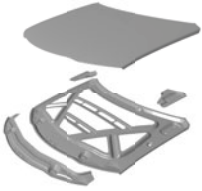
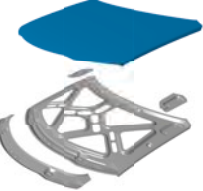

The project kicked off with extensive research work, in which the state of the art for both aluminum and steel hoods in the mid-size and upper mid-size class was determined. The steel reference hood developed for InCar plus is oriented towards the best hoods in terms of global stiffness and oil canning.

Pedestrian protection is an important criterion in the design of a hood. All hood variants are therefore subjected to impact simulations according to the Euro NCAP process. At 168 measuring points on the front structure of a vehicle, an example dummy head impact is used to determine how compatible the structure is with the objectives of pedestrian protection. The InCar plus reference hood and all of the studied concepts offer the potential for five stars even without active measures such as raising the hood using accordingly designed hinges.

LITECOR OUTER PANEL WITH WEIGHT-OPTIMIZED INNER STRUCTURE

The outer hood panel manufactured using the Litecor steel-polymer composite displays outstanding stiffness properties and low weight per unit area. Thus, it is 2.9 kg lighter than the outer panel of

Hood benchmark						
Segment	Mid-size			Upper mid-size		
Material	Steel			Aluminum		
Weight	20.4 kg	20.1 kg	20.9 kg	11.0 kg	12.2 kg	13.7 kg
Weight per unit area [kg/m ²]	11.0	10.9	11.6	5.7	6.2	6.9

InCar [®] plus	InCar [®] plus reference	InCar [®] plus solution LITECOR [®]	InCar [®] plus solution steel-magnesium hybrid
Design			
<ul style="list-style-type: none"> Steel LITECOR[®] Magnesium 			
Weight	19.3 kg	14.9 kg	11.3 kg
Weight per unit area [kg/m ²]	10.2	7.9	6.0

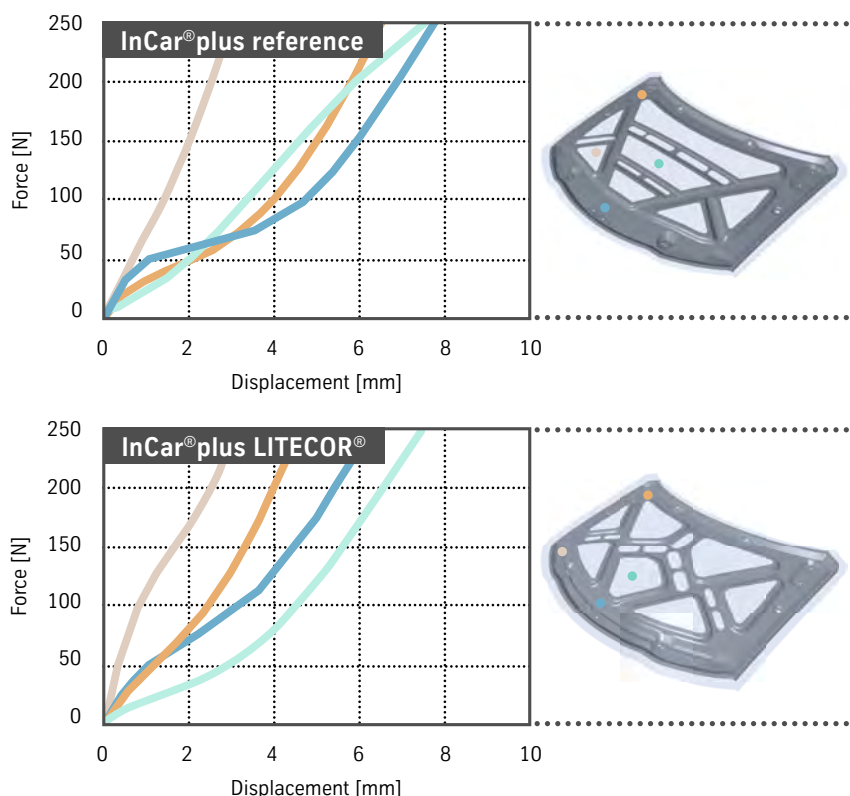
❶ Benchmark of hoods (top) and InCar plus hood concepts (bottom)

the reference hood. The inner structure also offers further potential for reducing weight. In comparison with the reference outer panel's sheet metal thickness of 0.70 mm, the Litecor layer structure is slightly larger, with an overall thickness of 0.85 mm, thus offering higher resistance to oil canning. As a result, the inner structure can be adapted by reducing the sheet metal thickness and optimizing the strut design. In comparison with the reference structure, this reduces the weight by a further 1.5 kg. In total, the hood with Litecor outer panel and optimized inner part is therefore 4.4 kg lighter than the reference.

STRUCTURE-MECHANICAL DESIGN

The Litecor hood with weight-optimized inner part was tested as regards the load cases of torsional stiffness, front lateral stiffness, longitudinal stiffness and rear lateral stiffness. It meets the global stiffness target values. The high level of oil canning resistance which is achieved is similar to that of the reference hood, ②.

The Euro NCAP pedestrian protection assessment is undertaken virtually on the overall vehicle. Potential for a five-star rating is achieved in consideration of the HIC values (Head Injury Criterion) of all 168 impact points. Rig tests were performed on prototype hoods to validate the virtual development. The test results reveal a good match with the simulation, ③.

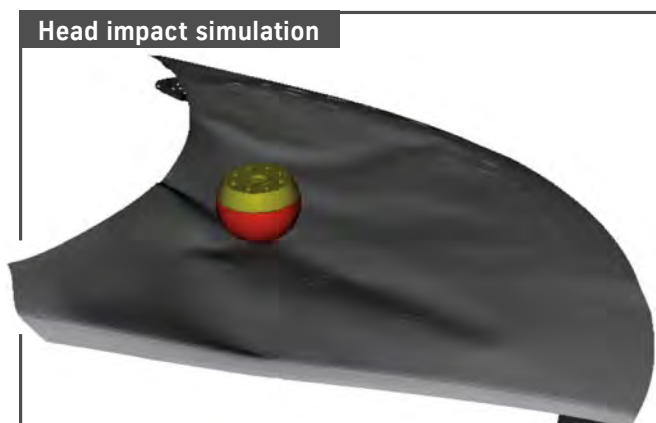


② Oil canning resistance of the reference hood (top) and the Litecor hood (bottom)

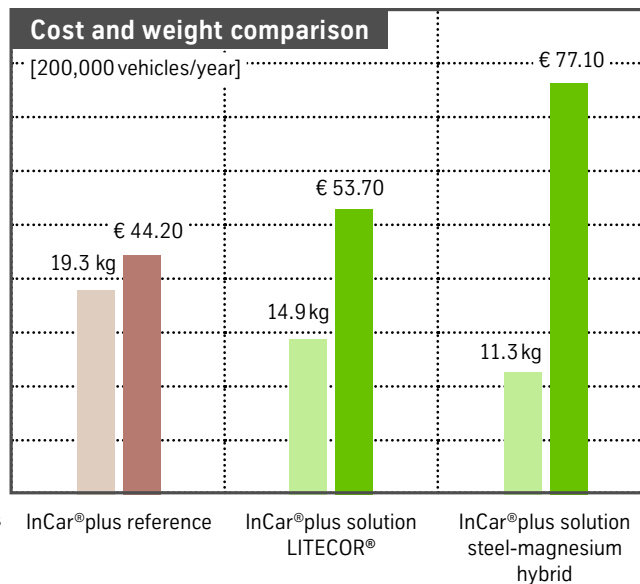
MULTI-MATERIAL DESIGN AS A CONCEPT

One innovative option for saving weight is the combination of magnesium sheet metal for the inner structure and very thin but higher strength sheet steel for the outer panel. Thanks to the low density of magnesium, a hood with this multi-material design weighs just 11.3 kg, around 8 kg less than the reference.

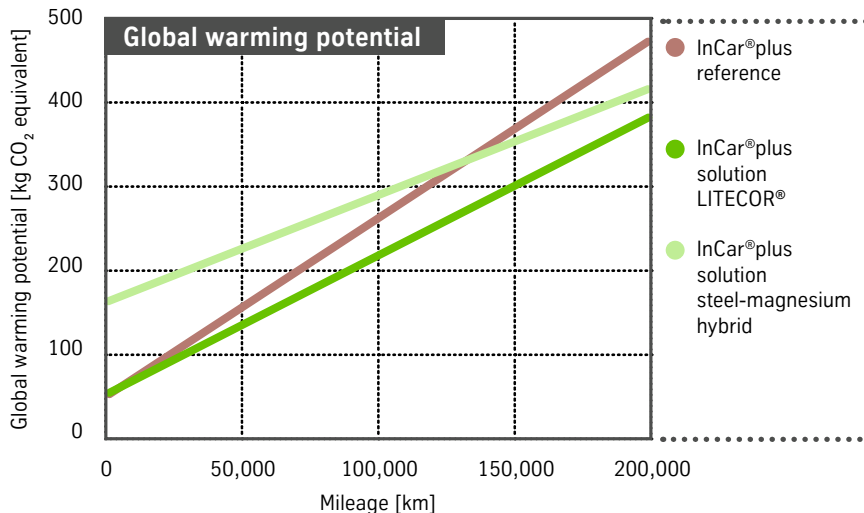
ture and very thin but higher strength sheet steel for the outer panel. Thanks to the low density of magnesium, a hood with this multi-material design weighs just 11.3 kg, around 8 kg less than the reference.



③ Comparison of simulation (left) and test (right)



④ The InCar®plus solutions offer a weight advantage of up to 8 kg per hood



⑤ Both InCar®plus solutions are better than the reference in terms of global warming potential

The extensive lightweight design potential is concealed beneath the outer panel in the form of an optimized inner hood structure. A honeycomb geometry supports the outer panel over its entire area, thus enabling especially thin steel sheets to be used for the outer panel. This newly developed concept offers good oil canning performance even with an outer panel which is only 0.50 mm thick. The global stiffnesses correspond to the target values. Potential for a 5-star rating is achieved in Euro NCAP pedestrian protection.

ThyssenKrupp has extensively tested the technical manufacturing feasibility of the magnesium sheet component. Magnesium is formed at a temperature of

approximately 240 °C in a heated die. A forming simulation confirms that the magnesium sheet components can be manufactured.

The magnesium sheet hinge and latch reinforcements can be joined to the inner magnesium panel using spot welding. The cycle times are around 0.4 to 0.65 s per spot weld and are comparable with those of steel components. The outer panel, consisting of extremely thin steel sheet, is joined to the inner magnesium sheet structure by means of table-top hemming. Additional corrosion protection is also required for the magnesium sheet components. In this case, multi-layer wet coating for high corrosion requirements is used.

As the mechanical and thermal properties of steel and magnesium are different, a material-friendly design is vital. Larger cross-sections in the surrounding profiles enable individual adaptation of the global stiffness to customer requirements. To ensure that the hood continues to meet the pedestrian protection specifications, specific weakening of the profiles by means of slitting is possible.

ATTRACTIVE COSTS, POSITIVE OUTLOOKS

Both concepts have been extensively evaluated in terms of manufacturing and costs, and are suitable for integration into the conventional body-in-white. Detailed body-in-white planning together with a cost breakdown is available for each concept, ④.

Litecor hemming only requires minor adaptations to the table-top hemming system. Roller hemming may also prove sensible for small quantities.

In total, lightweight design costs of less than € 2.20/kg are incurred for the Litecor hood. In the multi-material concept, the material costs for the magnesium sheet and its further processing lead to lightweight design costs of € 4.11/kg.

Both concepts have been analyzed as regards their environmental compatibility, ⑤. If raw material acquisition, material manufacturing and recycling are included in the balance, both solutions are ecologically very attractive.

Litecor's suitability for use in production has already been successfully demonstrated in the hood fitted on the VW Polo World Rally Car. In the medium-term, Litecor is initially to be manufactured on a large scale for inner parts. This will be followed by visible components with outer panel quality.

LIGHTWEIGHT DESIGN IN THE DOOR OUTER PANEL

Innovative steel products reduce the outer panel weight of planar components such as the doors by up to 33 % – without any loss of oil canning or dent resistance and at very attractive lightweight design costs of just € 2.25/kg. ThyssenKrupp has verified the suitability of the Litecor steel-polymer composite for large-scale production using the example of a side door.



① Lightweight Litecor door, sandwich structure 0.25/0.40/0.20 mm

Inexpensive lightweight doors are particularly required in the volume market, as the high costs of aluminum prevent its use here. As a reduced outer panel sheet thickness leads to the loss of oil canning and dent resistance, this has to be compensated. To do this, ThyssenKrupp has studied the Litecor steel-polymer composite in detail, ①. To enable an assessment of the state of the art, a benchmark involving measurements on eight standard doors was first undertaken. Oil canning and dent resistance were the significant assessment criteria in this, ②.

The InCar plus doors are oriented towards the best standard doors in the benchmark in terms of oil canning and dent resistance. 67 points at which oil

canning is investigated in detail by means of simulation are defined on the InCar plus doors. Oil canning and dent resistance are additionally measured at ten selected points on the test rig. Good correlation between the simulation and test was revealed on the whole.

DOOR CONCEPT WITH LITECOR

The Litecor steel-polymer composite, consisting of two very thin steel cover sheets and a plastic core, was developed specifically to improve oil canning. The Litecor outer panel reveals performance comparable with that of the reference with a weight reduction of 33 % at the same time, ③.

Door benchmark											
Segment	Small car		Compact class		Mid-size	Upper mid-size			InCar®plus reverence	InCar®plus solution	
Material	Steel				Aluminum			Steel	LITECOR®		
Qualitative assessment of oil canning	●●○	●○○	●●○	●○○	●●○	●●●	●●○	●○○	●●●	●●●	
Qualitative assessment of dent resistance	●●●	●○○	●●○	●●●	●●○	●●●	●●●	●●●	●●●	●●●	
Outer panel sheet thickness [mm]	0.69	0.70	0.67	0.75	0.72	0.75	1.02	1.01	0.75	0.85	
Outer panel weight [kg]	4.1	3.7	4.0	4.7	4.2	4.8	2.6	2.8	4.9	3.3	

●●●

●●○

●○○

Performance level

↑

② Door benchmark and comparison with InCar plus reference door and InCar plus Litecor door

The forming behavior of various materials under near-production pressing conditions can be determined on the basis of a modular tool which simulates the area of the door handle recess. In addition to Litecor, a conventional bake hardening steel CR210BH and aluminum from the group of 6000 alloys are being studied in the first test series. The styling edges, which are becoming increasingly striking on vehicle doors, can be easily implemented with Litecor. This composite material offers greater design freedom in comparison with aluminum.

LITECOR FORMING SIMULATION

For Litecor, forming simulation for the entire manufacturing process chain is extremely important as a basis for manufacturing planning at the customer. New products must be easy to integrate into the customers' CAx landscape. To achieve this, product-specific solutions which can be implemented on an industrial scale are being developed in close cooperation with software manufacturers. To obtain realistic predictions, the other characteristics of the polymer core layer have to be taken into consideration in the Litecor forming simulation in addition to the characteristics of the steel cover sheets. In the past, this was only possible very inadequately or with extensive modeling effort, and was unsuitable for analyzing the entire process chain. While shell elements for the steel cover sheets and volumetric elements for the polymer core layers are suitable for characterizing the Litecor-specific properties, they are limited to the 1st forming stage, as the software available on the market does not (yet) offer any trimming options for volumetric elements. Subsequent operations such as post-forming, hemming or beading cannot therefore be simulated. A mill bar model which meets the necessary requirements was developed on this basis in close cooperation with software manufacturers. This is now available to the ThyssenKrupp Group. The high forecasting accuracy of the above described method has already been verified on various test and production components and has been used successfully for numerous feasibility analyses, ④.

Following successful forming simulation of the entire Litecor manufacturing chain, further development is now focusing on advanced grid refinement algo-

rithms to reduce computing time. This is the prerequisite for economical use in highly complex processes involving hemming operations, for example.

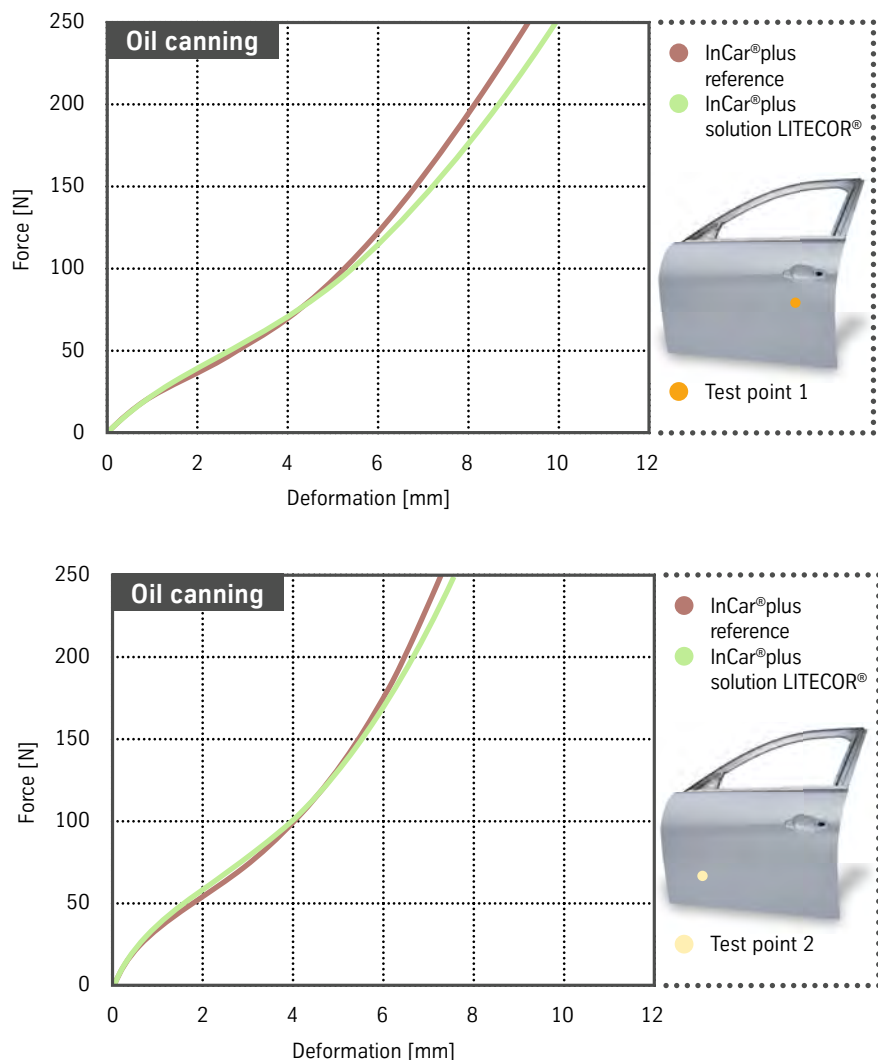
The usual processes for joining the outer panel to the inner structure are table-top hemming (machine hemming) and roller hemming with a robot. Both hemming processes are state of the art for steel and aluminum materials. Due to the material's high stiffness, however, special adaptations are required for the Litecor composite to achieve a flawless hemmed joint. ThyssenKrupp has developed a simple and effective solution for table-top hemming: a groove in the bending die which specifically influences the material when bending the outer panel. The groove leads to the formation of a defined, softer area in the inner fibers during bending. This consequently enables lon-

gitudinal compensation in the inner fibers during the first hemming step so that the tensile fibers are relieved in the outer hemming process. This avoids cracks. This modification to the hemming tool has no influence on the processing of monolithic metal sheets.

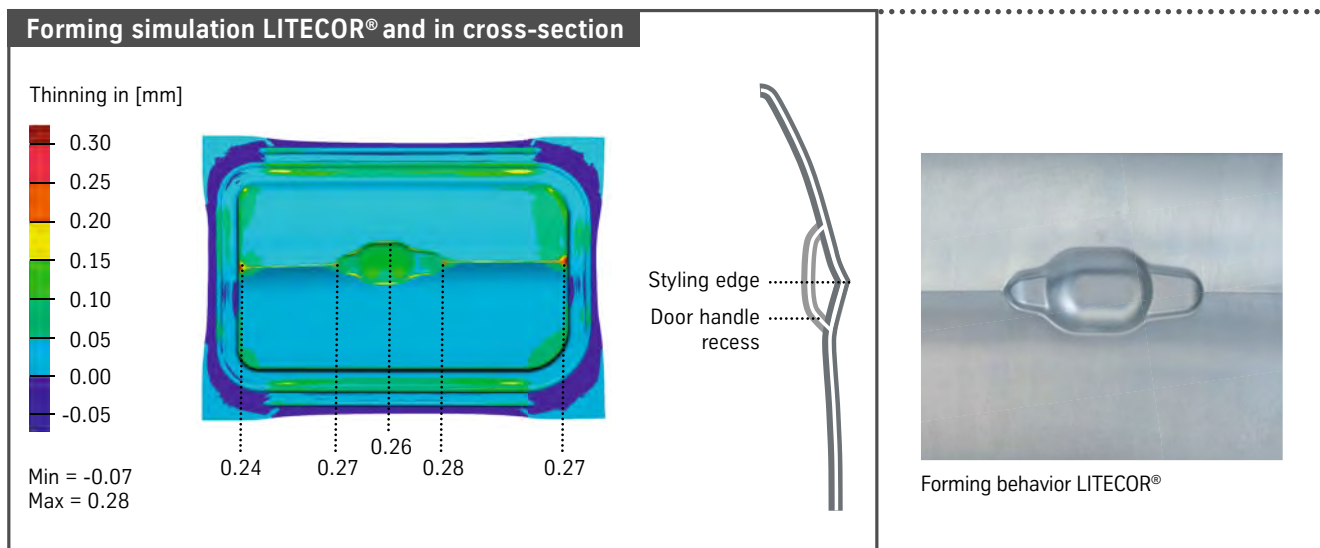
Process consistency and therefore production fitness for hemming Litecor were verified on a newly developed table-top hemming system which is suitable for use in volume production, ⑤.

NEW TABLE-TOP HEMMING TOOL

As well as additional functions in the machine, the focus was primarily on the requirements posed by Litecor during development of the new table-top hemming system. Precise control of the process variables "force" and "position"



③ Comparison of oil canning performance at two test points



4 Simulation of the forming capacity of Litecor (left) and actual forming behavior (right)

deserve a special mention here. Besides these technological improvements, the topic of saving energy was also a major objective in further developing the hemming machine. The use of controlled electric drives and extensive omission of the usual pneumatic drives are also making a significant contribution towards reducing the energy requirements and costs of operating equipment. Cycle time optimization below the usual times is also likely.

The doors can be hemmed with constant quality and without cracking within the usual body shop cycle time. Geometries similar to those of conventional steel doors can be produced, and only minor additional adaptations to the hemming system are necessary. Besides the geometric adaptations for the pre-hemming operation, the defined hem-

ming force with holding time in the finish hemming position deserves a mention here.

ROLLER HEMMING WITH LITECOR

However, the method applied for Litecor during roller hemming with the robot is a different one, as the forming processes are carried out only partially and not over on the entire circumference. The task is not to avoid cracking in the outer fibers but to reduce waviness in the closed flange. To achieve this, the roller application points on the component differ from those which are usually used; secondly, a further pass may be necessary for smoothing with the robot. Hemming capability with the robot has been verified on individual prototype parts.

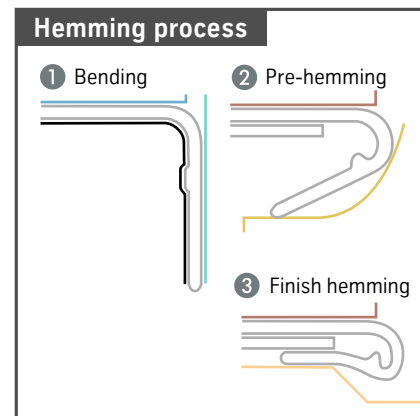
COST COMPARISON AND POSSIBLE APPLICATIONS

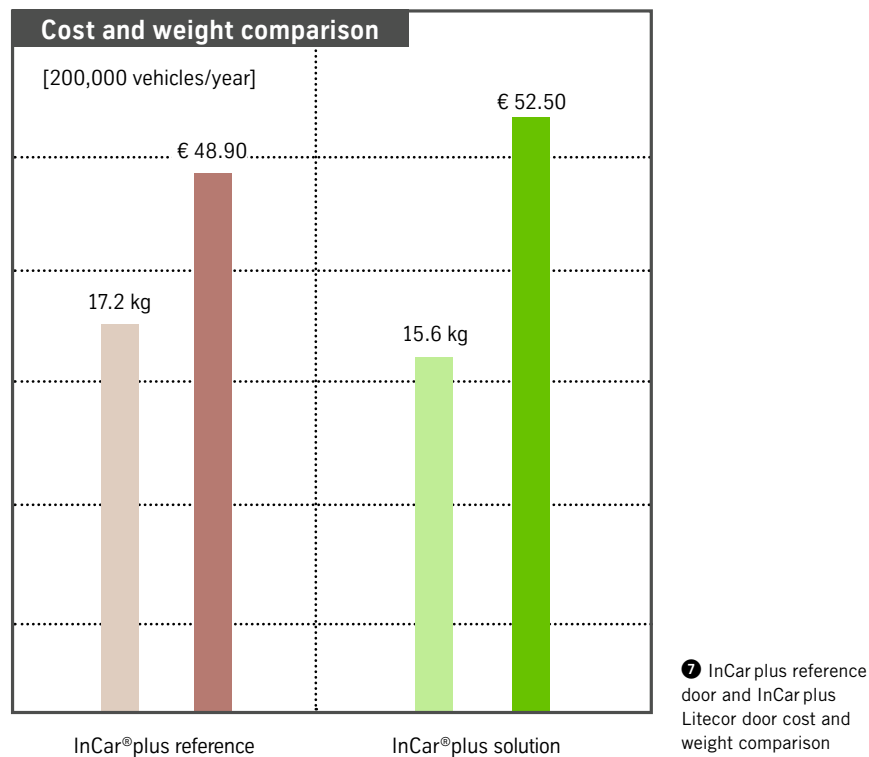
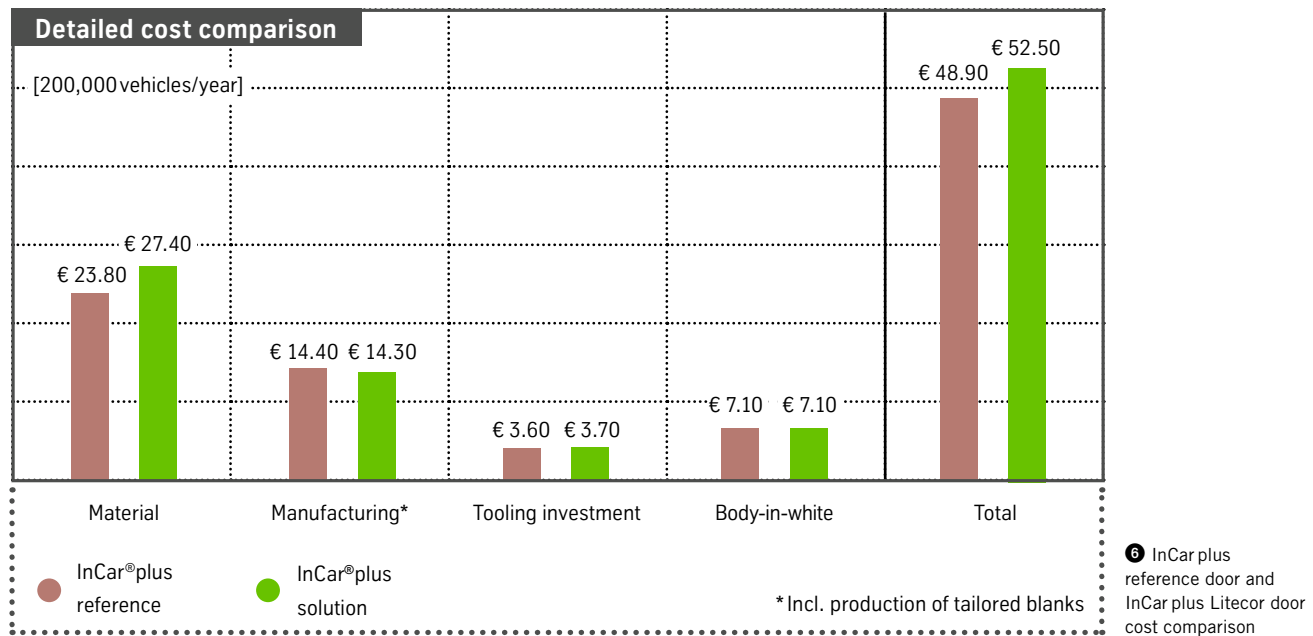
In the outer panel, the Litecor steel-polymer composite reduces the weight per door by 1.6 kg with attractive lightweight design costs of € 2.25/kg, 6 and 7. In addition, this concept can be implemented virtually without adapting the manufacturing process at the OEM. Only the table-top folding tool requires a minor modification.

The Litecor composite application studies were undertaken using the example of the door outer panel, but can also be transferred to other outer panel components such as the hood, trunk lid or roof. Litecor is also suitable for components in the body's inner structure, e.g. in the vehicle floor. Large-scale production of Litecor for



5 Mechanical hemming system and process steps





inner parts is planned in the medium term. Production for outer panel components is then intended.

OUTLOOK

The use of very thin metal sheets in the outer panel is another option for building

especially light steel doors. The necessary reduction of oil canning and dent resistance can be compensated by specifically applying PU-based plastic as a backing.

A spray mixing head specifically applies the reactive mixture onto the surfaces. The hybrid material's proper-

ties can be specifically adjusted by selecting different PU formulations, using additives which promote stiffness and applying a variable number of layers, thus achieving maximum lightweight design with outstanding performance at the same time. The weight reduction in comparison with the reference door will be up to 1.5 kg.

In the manufacturing process, the plastic layer(s) is (are) sprayed on directly after pressing the outer panels to simplify complex handling of the very thin and therefore sensitive components. The PU plastic is hardened and heat-resistant a few seconds after application. These characteristics are of enormous importance during subsequent cataphoretic painting. Studies have proved that the plastic does not contaminate the cataphoretic painting bath and retains its adhesion and stiffening effect at 180 °C for 60 min in the oven.

Practical tests on the dent test rig reveal oil canning resistance comparable with that of the InCar plus reference door. Due to its acoustic advantages, the outer panel, which consists of thin, plastic-backed metal sheets, also has the potential to achieve comparable performance with just a few secondary acoustic measures. As a result, further weight reductions can be achieved. A cost forecast for this concept indicates lightweight design costs of around € 2.0/kg.

ECONOMIC LIGHTWEIGHT STEEL SEAT STRUCTURES

Seat structures are particularly important for lightweight design since, with an average weight of around 12.5 kg per seat, they are responsible for a total mass of 40 to 60 kg in the vehicle. By using new steel grades, seat components can be designed up to 15 % lighter without additional costs. In the cushion pan, a new composite material such as Litecor gives access to lightweight potential of up to 30 % with lightweight design costs of less than € 3/kg.

The development of seat structures has to fulfill different requirements. In InCar plus, new materials are studied as regards their suitability for seat structures, particularly in terms of the blue highlighted characteristics in ❶. A clear trend towards lightweight seat structures using high-strength steels and mixed material designs can be seen. At the same time, there is enormous cost pressure on seat structures.

A manufacturer-neutral seat structure, which corresponds to the state of the art in terms of design, weight and materials, was developed to determine the lightweight potential, ❷. The reference is a four-way front seat with a weight of 12.3 kg consisting of a steel structure with rails and mechanisms. The front seat is of a modular design to meet the increasing requirements of weight reduction, crash safety and package with increasingly shorter times to market.

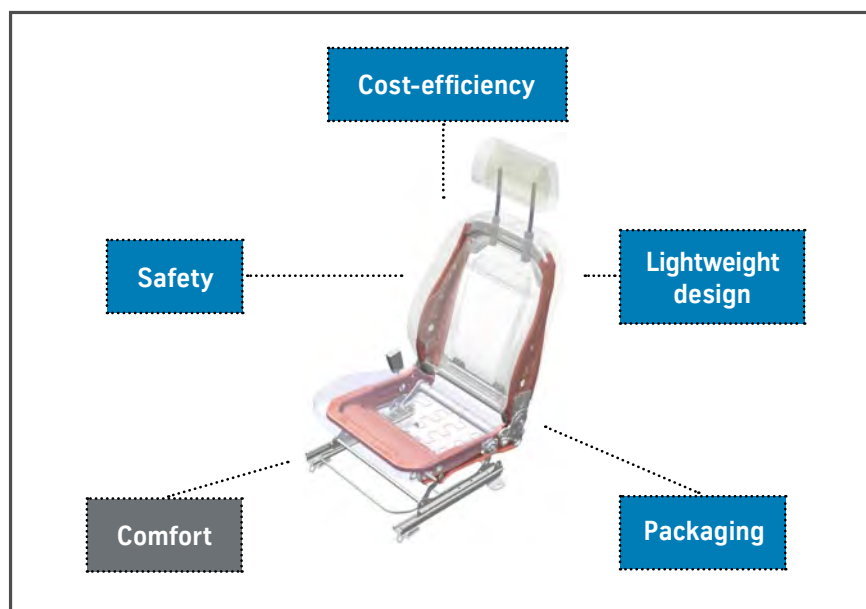
The following load cases were investigated to guarantee the crash safety of the reference seat structure: legal requirements (e.g. ECE-R14, ECE-R17, FMVSS 225), frontal and rear-end crashes with vehicle pulses from the InCar plus reference structure (for US NCAP and FMVSS 301) and misuse load cases (e.g. a knee test for the front seat cushion pan). In a vehicle crash, stress on the occupant in the form of forces and acceleration values firstly has to be minimized through energy transformation. Secondly, the

seat structures must deform in a controlled manner and ensure sufficient survival space for the occupant.

DEVELOPMENT OF SEAT BACKRESTS

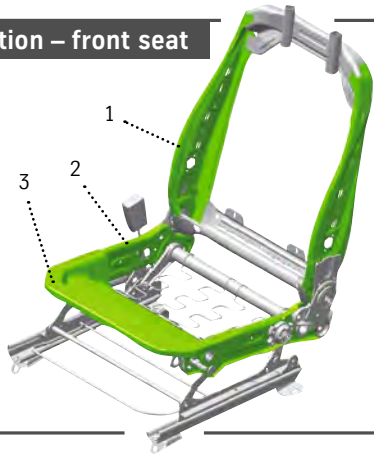
Concept development is focused on structural components, not the mechanisms. In a rear-end crash, the front seat backrest is stressed by the passenger, and by the load in a frontal crash.

Accordingly, both of these crash load cases are taken into consideration for the backrest in concept development. So that the concepts reveal performance comparable with that of the reference, the backrest side members consist of stronger materials but have a reduced wall thickness. The two concepts using the MHZ 500 and DP-K 590Y980T steel grades therefore achieve comparable performance with the same geometry. To prevent the backrest from buckling in



❶ Seat development requirements

InCar®plus solution – front seat



No.	Part	Material	Thickness
1 Backrest side member			
	Reference	CR420LA	1.10 mm
	Concept 1	MHZ 500	1.00 mm
	Concept 2	DP-K® 590Y980T	0.90 mm
	Concept 3	DP-K® 700Y980T	0.80 mm
2 Cushion side member			
	Reference	SCALUR® S550MC	1.60 mm
	Concept 1	CP-W® 660Y760T	1.50 mm
	Concept 2	HSM700HD	1.50 mm
3 Cushion pan			
	Reference	CR380LA	0.80 mm
	Concept 1	LITECOR®	0.20/0.80/0.20 mm

② InCar plus front seat component structure and material variants

the case of even higher strengths (DP-K 700Y980T) and further wall thickness reduction, the geometries of the backrest side members have to be modified. Mate-

rial formability is validated using simulations. One of the design challenges involved implementing the complex component geometry using a material

with this high strength class. By using ultra high-strength steel grades, it is therefore possible to achieve a weight reduction of up to 27 % in the backrest side member or 15 % in the backrest with neutral cost impact, ③.

ThyssenKrupp additionally validates the crash simulation with a component test derived from the overall seat simulation, ④. In this rear-end crash configuration (95-% dummy, InCarplus vehicle pulse), a maximum moment of around 3000 Nm is present at the backrest. The vehicle pulse was determined in advance from a vehicle simulation (in the rear impact load case). In turn, this acceleration-time curve is used for the seat design in the rear-end crash simulation.

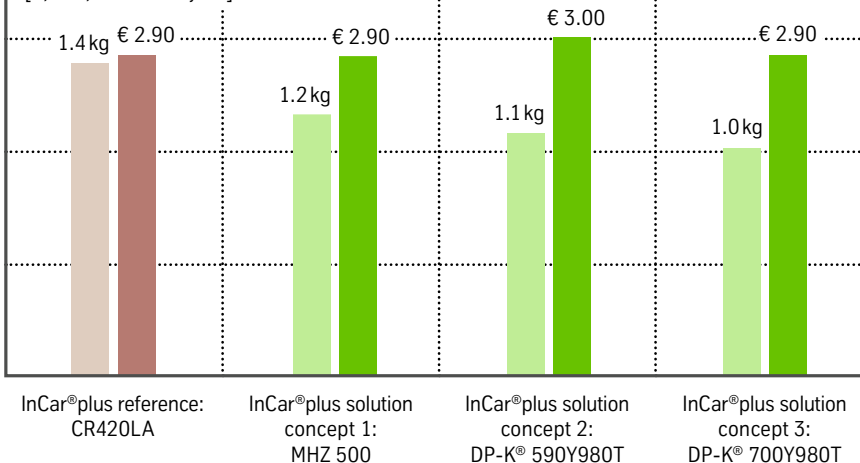
In-line with the overall seat simulation, a hydraulic cylinder is used to induce a force at the upper backrest crossmember in the component test. The backrest is bolted to the test rig with adjustment mechanisms. A good correlation for simulating the backrest moment arises from the comparison of the measured force-distance curves with the calculated diagrams, ⑤.

If the component test confirms the good correlation of CAE modeling with the test, a meaningful overall seat simulation result can also be assumed. The latter determines crash performance comparable with the reference for all lightweight concepts.

The joining situation is also assessed, e.g. the relevant materials' welding suitability and accessibility for welding

Cost and weight comparison

[1,000,000 seats/year]

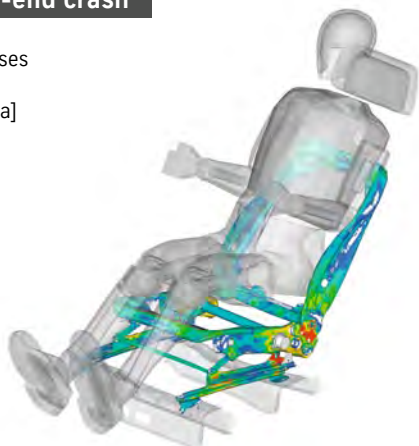
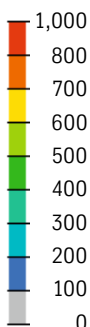


InCar®plus solution backrest side member

③ Depending on material, the newly developed backrest side member is up to 27 % lighter than the reference

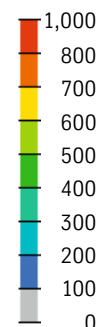
Simulation rear-end crash

Contour plot of stresses
(von Mises, max.)
Analysis system [MPa]



Backrest moment

Contour plot of stresses
(von Mises, max.)
Analysis system [MPa]



4 Derivation of the component test (backrest moment) from the simulation (rear-end crash)

robots or welding electrodes. Seat structures consist primarily of non-galvanized steels. The most frequent joining processes are laser beam, MAG and resistance spot welding. The investigated backrest concepts are designed for laser beam welding. To achieve the necessary tight tolerances, the different springback behavior is taken into consideration in the tool design.

DEVELOPMENT OF THE CUSHION SIDE MEMBERS

The cushion side members are subject to high mechanical stress and reveal a complex form due to the constricted package. Materials which combine high strength with comparably good ductility are ideal. One forming criterion of relevance to these components is low edge cracking sensitivity, which is tested using hole widening tests in the laboratory. Low edge cracking sensitivity also increases the feasibility of collared grooves, which are often used for assembly with neighboring components such as the transverse tube. Due to the design, joining concepts other than collar grooves are used in the example described here.

The cushion side member in the reference consists of Scalur S550MC. The two InCarplus concepts consist of CP-W 660Y760T and HSM700HD materials. They offer crash performance comparable with that of the reference. Component feasibility was ensured through forming simulations and confirmed by

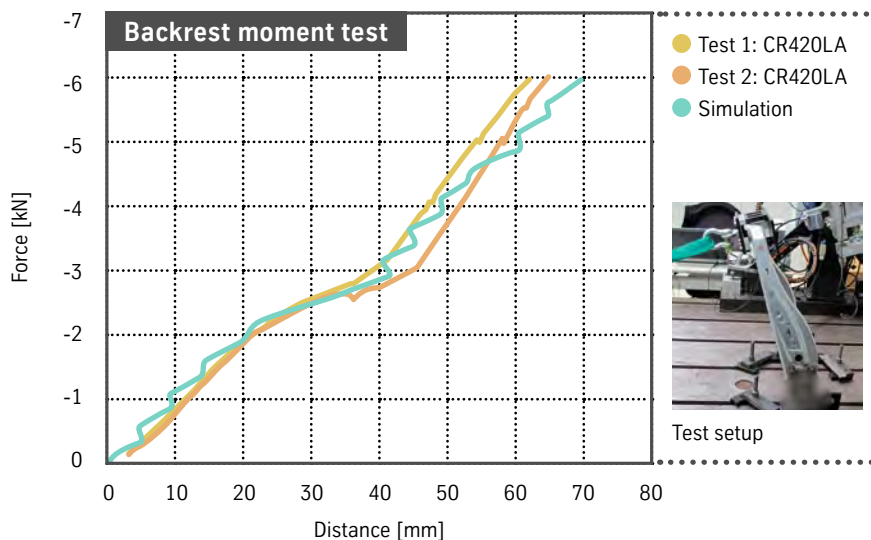
manufacturing prototype components, 6. The use of ultra high-strength steels enables weight to be reduced by up to 6 % here.

As adjacent components such as transverse tubes or recliners are primarily mechanically connected to the cushion side member, the joining assessment is restricted to the MAG weld between the cushion side member and the cushion pan.

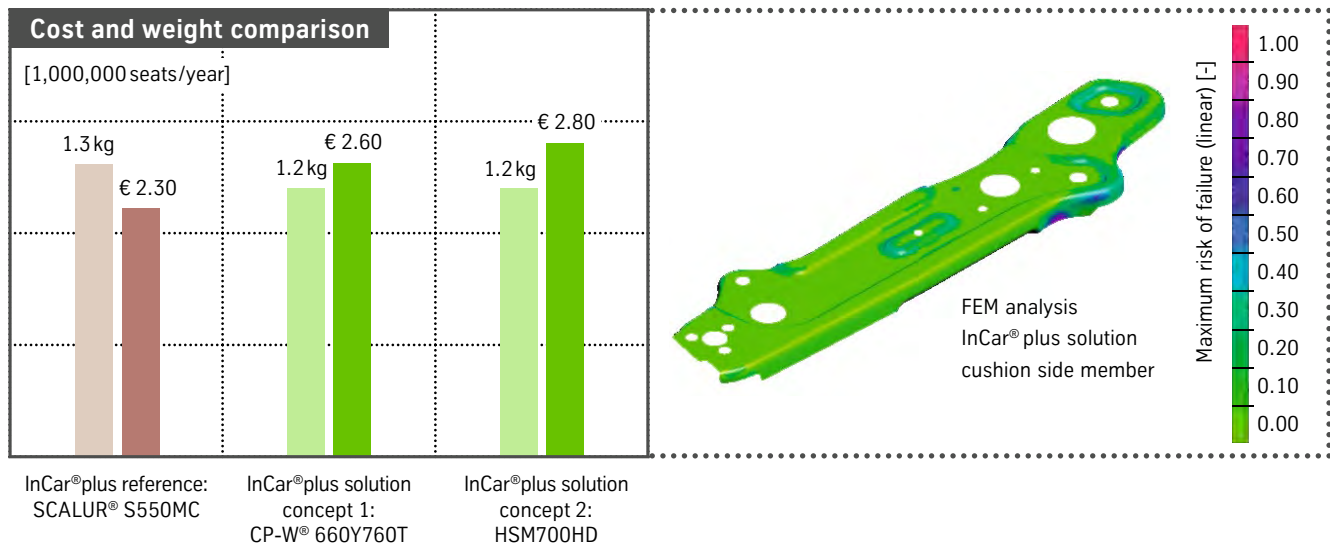
DEVELOPMENT OF THE CUSHION PAN

In a frontal crash, the seat side member, together with the seat belt and the air-bag, must prevent the occupant from

slipping beneath the belt (anti-submarining). The front transverse tube transmits the main load in this case; the cushion pan is subject to planar stress. The Litecor steel-polymer composite with cover sheets consisting of CR210IF (a higher strength IF steel) and an 0.8 mm plastic core layer is therefore recommended for this component. The two cover sheets are each 0.2 mm thick. In addition to the overall seat simulation, a misuse test is also simulated to design the cushion pan concept. In this knee test, it is assumed that the occupant is kneeling on the seat. The cushion pan must not deform plastically. The Litecor composite achieves performance compa-



5 Backrest torque moment result and test setup



6 Forming simulation (right) and results (left) for cushion side member

table with that of the reference in this misuse test. The weight reduction is 37 % with additional costs of just 31 %.

As a composite material such as Litecor leads to specific joining requirements, concept development is focused on the joining situation. The cushion pan and cushion side members are best joined with semi-tubular punch rivets and adhesive bonding or by means of resistance spot welding. The joining concept, which differs from that of the reference (reference: MAG welding), necessitates a slightly modified component geometry to guarantee accessibility for the joining by hollow self-piercing rivets, 7.

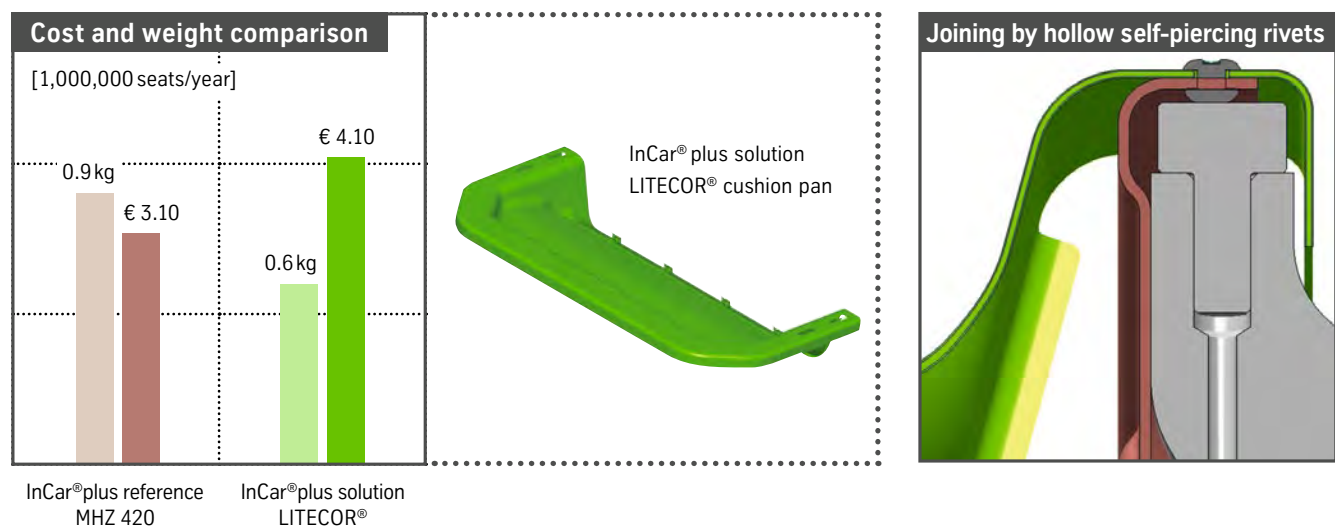
In addition to the connection of the cushion pan to the cushion side member, the connection from the cushion pan to the spring mat was also investigated in the joining assessment. The spring mat is hooked in at the front of the cushion pan and joined to the transverse tube at the rear, and influences seating comfort. In the Litecor concept, the connection to the spring mat was geometrically modified slightly due to strength reasons.

In deviation from the usual cost calculation procedure (see article "Benchmark 2.0: the Updated Reference Structure" from page 86), an estimated quantity of 500,000 vehicles or one million vehicle seats per year is used as the basis for the

seats. The reason being that modular seat structures can be used for several vehicles with minor modifications.

REAR BENCH SEAT CONCEPT DEVELOPMENT

While front seats reveal an identical or comparable structure across all model variants, rear seats have to meet considerably more complex requirements. These range from high comfort, e.g. in the form of adjustable individual seats, to very high flexibility such as in the form of rear seats with a flat loading floor. As the front seat concepts can be transferred to individual seats in the rear



7 Cushion pan cost and weight comparison (left), component representation (center) and sectional view of joining by hollow self-piercing rivets (right)

area in part, a rear bench seat which can be split 40:60 with a flat loading floor is selected as the reference for the rear. It has a modular design; its seat structure weighs 12 kg. The modular structure offers the advantage that the rear bench seat can be adapted quickly to different body dimensions.

To achieve a good flow of force at the front seats, the belt anchor points are connected to the body wherever possible. The belt is not integrated into the seat; instead, the belt retractor is mounted in the B-pillar and the belt buckle and belt end fitting are connected to the seat rails.

In the design of the rear bench seat, it was decided to integrate the belt mounting for the center passenger into the backrest due to reasons of comfort and not, as in other vehicles, into the cross-member or the vehicle roof. However, this results in high stress on the seat structure. In the ECE-R14 static load case, for example, the test pieces introduce forces of up to 13.5 kN into the belt system while the permissible deformation is limited at the same time.

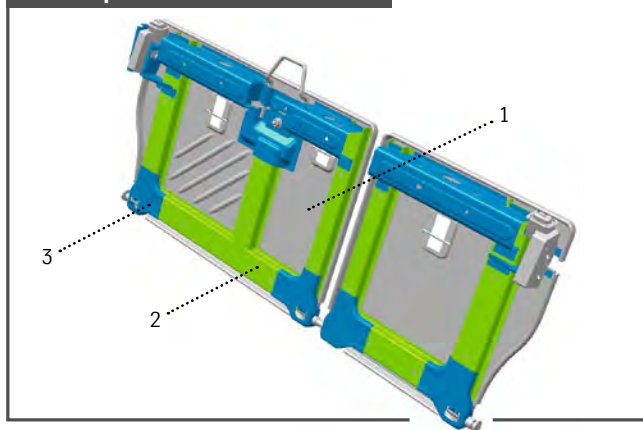
Crash requirements must be met as well as fulfilling the static load cases. In the "protection against load" load case (ECE-R17), for example, two load cubes, each weighing 18 kg, impact the rear bench seat at a speed of 50 km/h. This has to restrain the cubes, and its seat structure may only undergo limited forward displacement, ⑧.

The focus during concept development was therefore on the profiles and reinforcement brackets. The wall thickness of the profiles varies in the range from 0.80 to 1.00 mm and that of the reinforcement brackets in the range from 2.00 to 2.50 mm. In-line with the front seat backrest, the wall thickness reduction limit was also reached in the rear bench seat profiles. Even thinner profiles would buckle and lead to impermissibly high deformation values. Geometric compensation through beads additionally increases the profiles' strength.

If the reinforcement brackets are manufactured from Scalur S550MC, their wall thickness can be reduced by 0.10 mm. The loss of stiffness is compensated through slight local changes in

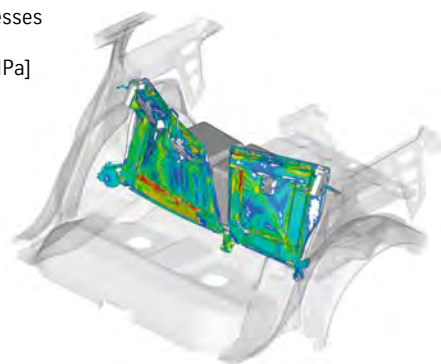
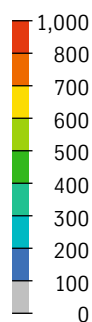
geometry. Again, the feasibility of both the reference and the concepts was validated through forming simulations here. In addition to static load cases (ECE-R14 belt anchorage test and FMVSS 225 to design child restraint systems), crash load cases (frontal/rear-end crash and ECE-R17) are also taken into consideration in concept development. In total, these measures lead to a weight saving of up to 15 % with favorable lightweight design costs.

InCar®plus solution rear seat



FEM analysis

Contour plot of stresses
(von Mises, max.)
Analysis system [MPa]



No.	Part	Material	Thickness
1	Rear seat panel		
	Reference	CR380LA	0.60 mm
2	Profiles		
	Reference	CP-K® 570Y780T	0.80 to 1.00 mm
	Concept 1	DP-K® 700Y980T	Δthickness of reference -0.10 mm
3	Reinforcement brackets		
	Reference	HR420MC	2.00 to 2.50 mm
	Concept 1	SCALUR® S550MC	Δthickness of reference -0.10 mm
	Concept 2	HSM700HD	Δthickness of reference -0.20 mm

⑧ Rear bench seat: reference with "protection against load" simulation and representation of component variants

NEW WHEELS MADE OF STEEL — LIGHT AND STYLISH

Thanks to the combination of high-performance steels and innovative manufacturing technologies, ThyssenKrupp is developing lightweight wheels which are up to 20 % lighter than current production steel wheels. In parallel, this is leading to a modular design engineering principle for an attractive visual appearance and high design flexibility. The steel wheels which have been developed are lighter and less expensive than modern aluminum wheels as well as being more ecological over the life cycle as a whole. One further highlight is the 20-inch hybrid wheel manufactured from steel and carbon fiber reinforced plastic (CFRP), which sets new standards in terms of its concept, lightweight engineering and design.

A wheel serves to connect and to transfer power between the tire and axle and has to meet the highest standards of safety. During vehicle operation, it is subject to changing dynamic and abrupt stresses, which it has to permanently withstand throughout the life of the vehicle. The wheel must additionally guarantee appealing handling and be compatible with all add-on parts in the tightly delimited wheel area. Particular attention must be given to the weight of the wheel, as the negative effects of weight are threefold. For instance, the four wheels make a significant contribution firstly to the gross vehicle weight and secondly to the moved rotational masses, impacting unfavorably on fuel economy and CO₂ emissions. Thirdly, the wheels form part of the unsprung masses, which have to be minimized due to reasons of driving safety and ride comfort.

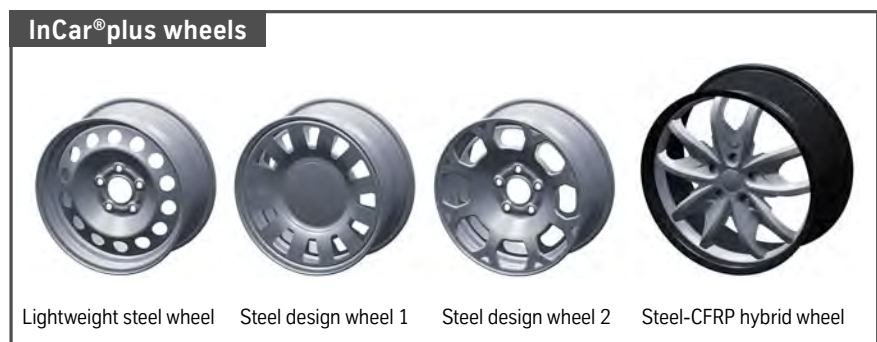
By no means least, the wheel is a prominent design feature on the vehicle. The appealing visual appearance of the wheel individualizes the vehicle and is often a relevant purchasing incentive for the customer. The wheel design additionally enables the OEM's models to stand out from the competition, ❶.

EXTENSIVE BENCHMARK AS THE BASIS FOR SUCCESS

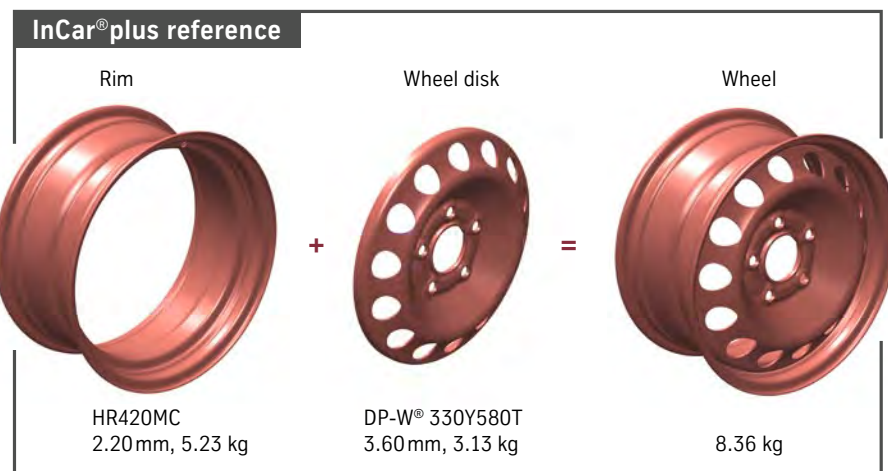
At the start of the development phase, the passenger car wheel market as well as the state of the art for passenger

wheels were intensively analyzed. A market study revealed that the typical steel disc wheel is installed primarily on cars up to the mid-size class and on vans. Aluminum wheels predominate as of the mid-size class and in wheel sizes of 17 inches and over. For a number of years, their market share has also been increasing amongst mid-size class and

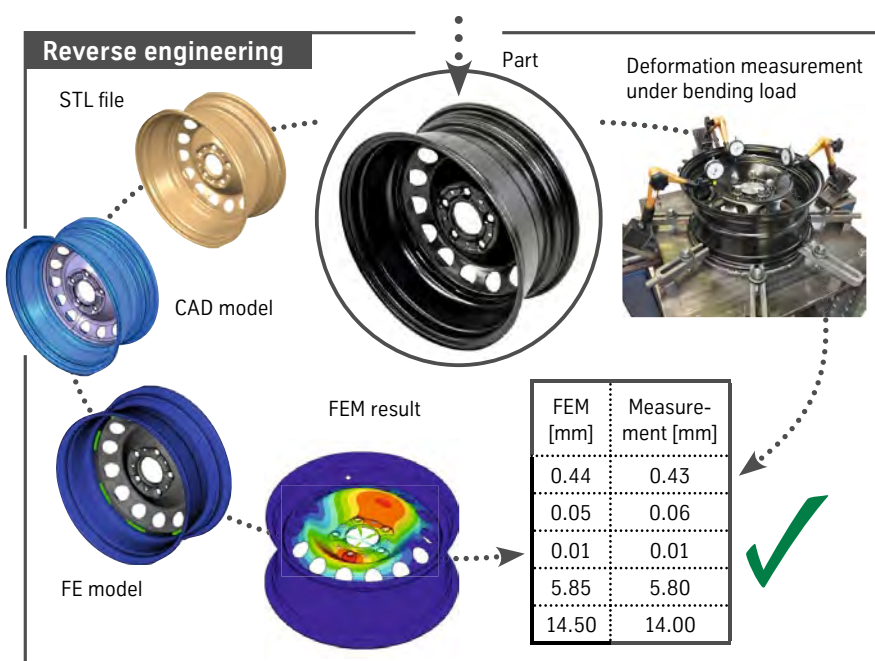
compact vehicles. It is noticeable that, in addition to numerous aluminum wheels, only one single classically designed steel wheel is frequently offered as part of a vehicle's original equipment, despite the fact that steel wheels are significantly less expensive than aluminum wheels, whose prices rise progressively as the wheel size increases.



❶ Overview of the steel wheels developed in the InCar plus project



② Initial basis for the InCar plus wheel innovations



③ Validation of the reference structure

The weight of 20 representative 16-inch wheels was analyzed in a benchmark. Astonishingly, it was discovered that cast aluminum wheels are often heavier than conventional steel wheels of the same size and load bearing capability. This is firstly attributable to the fact that a wheel manufactured from sheet metal represents the optimum design in terms of performance and weight. Secondly, focus on an attractive design often leads to additional weight.

The reference wheel for developing innovative wheels is also defined from

the benchmark. This involves the lightest and highest load bearing 16-inch steel production wheel with a width of 7 inches and an extremely low weight of just 8.36 kg, ②. It is therefore lighter than the comparable aluminum benchmark wheels of the same size and load bearing capability, which weigh up to 10.0 kg.

The performance of the selected reference wheel is experimentally determined in quasi-static and cyclical stress tests. The tests are oriented towards the legally specified test procedures and the tire

manufacturer's quality tests. The fatigue test under rotary bending loads simulates wheel stress on cornering at increased loads and focuses primarily on the wheel disc. The stiffness of the rim in the area of the rim flange is additionally measured to simulate the running test and deformation during tire fitting or curb impact in simplified form. The determined parameters form the target values for the new steel concepts. The reference wheel is measured digitally and was transferred to CAD. Thanks to this, the simulation tool results can be compared against the real reference wheel tests and therefore verified for the development phase, ③.

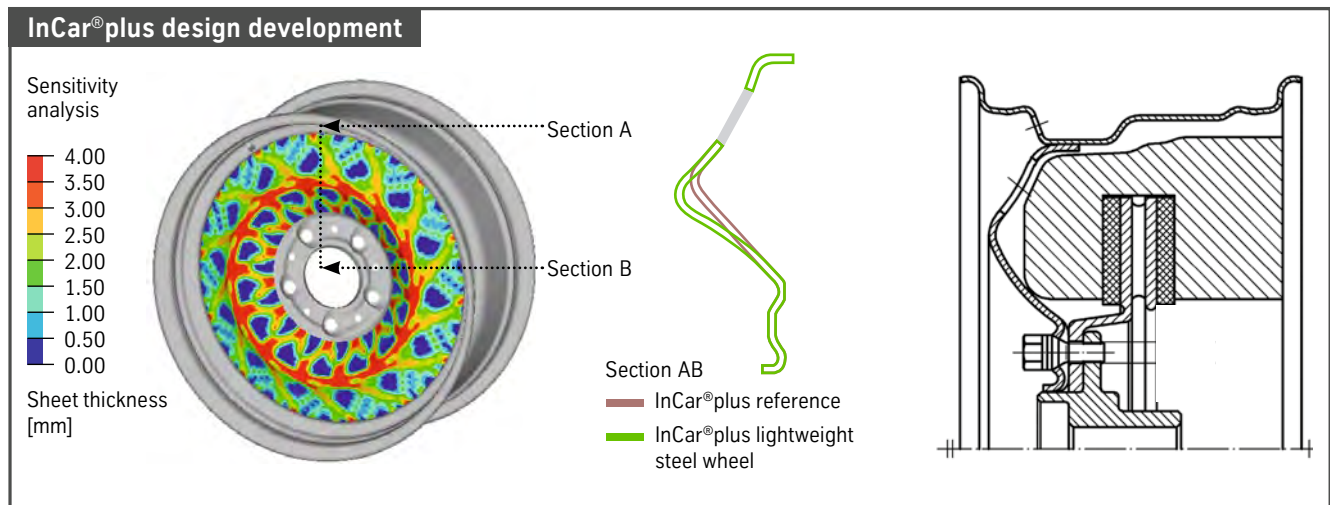
The requirement spectrum outlined so far makes high demands on the development of new steel wheels. InCar plus wheel development is therefore not only focused on the essential reduction of weight but also on the creation of design options for styling individual steel wheel looks.

LIGHTWEIGHT STANDARD STEEL WHEEL

Do these boundary conditions still offer scope for a new standard steel wheel? Resoundingly yes, because the weight of the wheel is reduced by up to 20 % thanks to the use of new materials and manufacturing technologies for the wheel discs as well as the flow-forming method for a stress-optimized rim. Initial component tests under cyclical stress show that hot-forming will be a suitable process for manufacturing the wheel discs in the future.

The potential weight saving has been analyzed separately for the wheel disc and rim. The wheel disc is subject to particularly high mechanical stresses. In this case, a lower sheet metal thickness acts directly on global component stiffness and thus vehicle handling. A reduction in sheet metal thickness therefore has to be compensated with geometrical adaptation. However, the very tightly packed installation space in the wheel area places tight constraints on such a new geometry, ④.

Numerical wheel disc sensitivity analyses show that the stiffening shaft exerts a significant influence on component stiffness. In the new lightweight wheel with cold-formed wheel disc, a "sharper-edged" stiffening shaft contour



④ Sheet thickness optimization (left), stiffness optimization through beading (center) and package restriction (right)

compensates the global loss of stiffening resulting from the reduction in sheet metal thickness. This design measure enables the sheet metal thickness to be reduced from 3.6 mm to 3.3 mm, leading to a weight advantage of 5 % for the wheel disc.

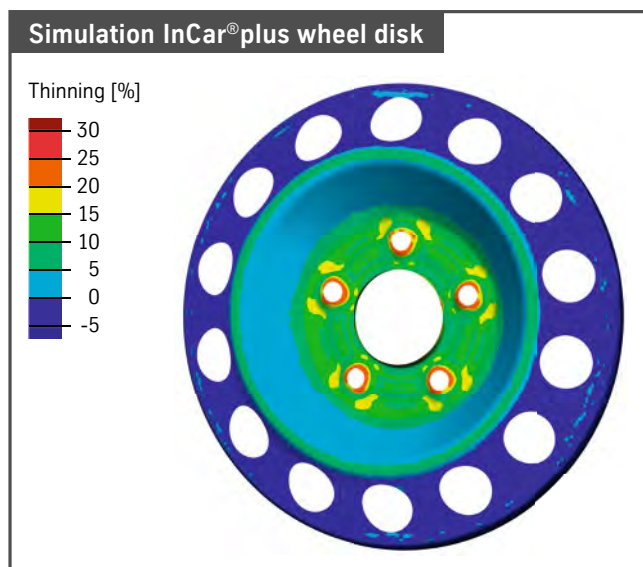
In addition, the reduction in sheet metal thickness is only possible using a material with a higher offset yield stress and fatigue strength under vibratory stresses, since the wheels' required fatigue strength still has to be guaranteed. However, the cyclical material strength from flat specimen tests can only be transferred to the wheel's com-

plex component behavior to a limited extent. As a result of this, the properties were investigated experimentally on the finished wheel under cyclical stress.

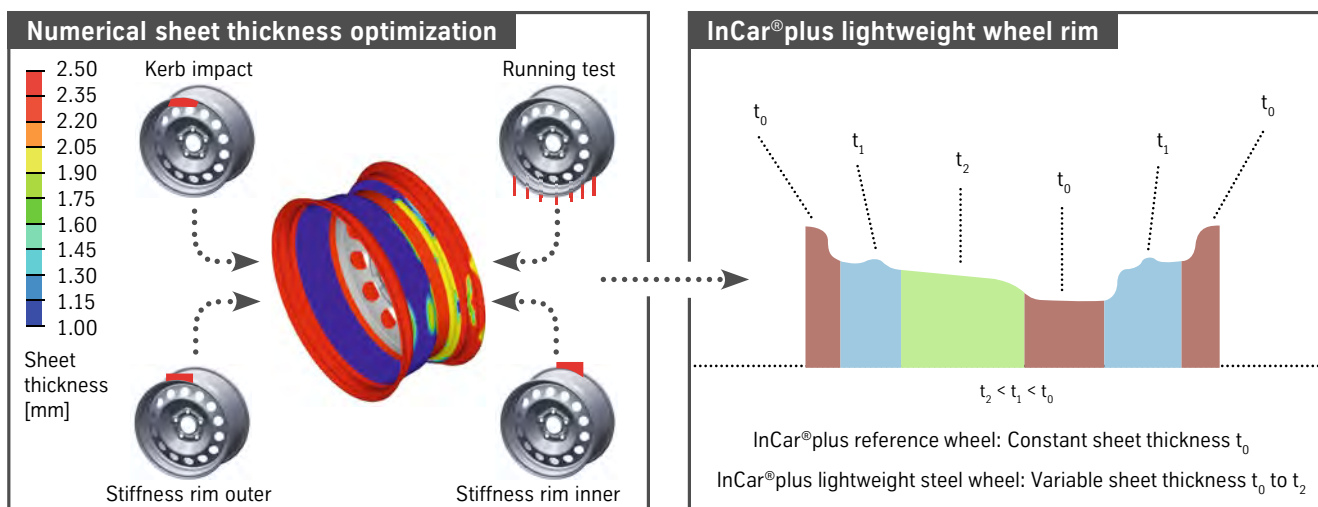
In parallel with the standard, cold-formed DP-W 330Y580T material, ThyssenKrupp is also investigating the suitability of further single and multi-phase steels in the 600-800 MPa strength class as well as an innovative composite material for the wheel discs. Promising steel materials for implementing a wheel disc which is both light and high-strength have been identified, enabling further conclusions to be drawn as regards significant material properties.

Even during the production of prototype wheels, the engineers ensure that the production processes are as close to the standard processes as possible to give consideration to certain effects on the component properties, e.g. the steels' edge cracking sensitivity or bake hardening effects. The various materials' pressings are accompanied by dimensional change analyses and are validated using the simulations performed in advance to design the process, ⑤. This enables the virtual assessment of possible usage beforehand.

An increase in offset yield stress and strength generally reduces the ductility



⑤ Validation of the forming simulation



6 Sheet metal thickness optimization on the rim and its results

of steel materials. To obtain a wheel disc which is light and can be freely designed, however, attaining a very high level of both ductility and strength is desirable. Hot-forming is a suitable process for accomplishing this. In this process, the initial mill bar is heated to an austenitizing temperature of around 900 °C and is then further processed in the hot-forming or hardening tool. This improved ductility at high temperatures enables complex components with high strengths. If partial press hardening is additionally applied, local differences in strength and ductility properties can be achieved.

INNOVATIVE WHEEL DISCS THROUGH HOT-FORMING

So far, no steel wheels are manufactured as standard using hot-forming. ThyssenKrupp is studying this promising process for the wheel discs and is evaluating it by means of cyclical stress tests on wheels. In comparison with the conventional cold-formed component geometry, the sheet metal thickness of hot-formed wheel discs can be reduced to 3.0 mm, as simulation calculations demonstrate. This leads to a weight saving of around 17 % in comparison with the cold-formed reference wheel disc.

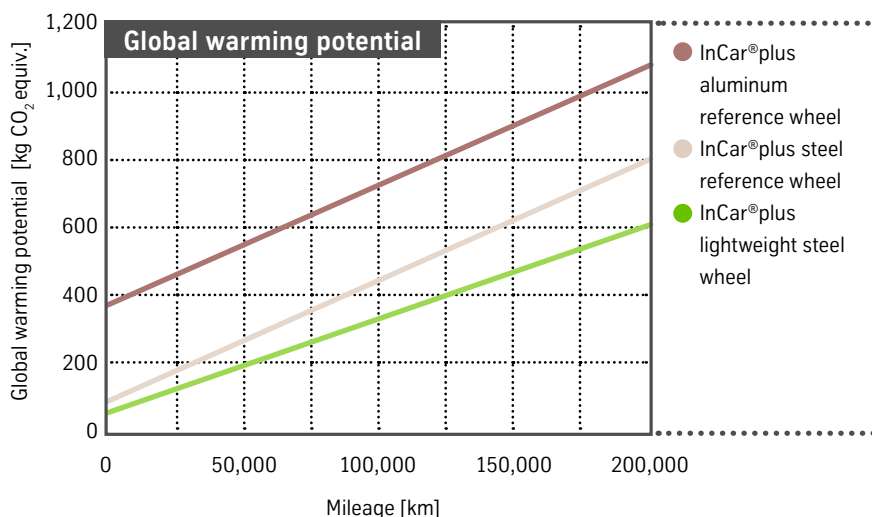
To attain an efficient hot-forming process without costly rework on the hardened component, all processing steps are integrated into one forming tool wherever possible. Particular attention must be paid to the wheel fastening in this

case. This is due firstly to the fact that the wheel bolt hole geometry is created using massive forming in volume production. Secondly, the wheel flange must reveal sufficient ductility, as high mechanical and thermal stresses occur here due to contact with the wheel bolts and the wheel hub. With its vast hot-forming know-how, ThyssenKrupp has succeeded in developing a prototype tool. This prototype tool can be used to manufacture hot-formed wheel discs in the direct process with local strength differences. Changed tool kinematics also enable complete press hardening of the wheel discs produced using innovative hot-forming steels and thus a reduction in cycle times.

RIM WITH DIFFERENT SHEET METAL THICKNESSES

The rim is the heaviest part of the wheel. In the reference wheel, it amounts to 62 % of the total weight. Added to this is the fact that weight which is located far away from the wheel's axis of rotation exerts a disproportionately high influence on fuel economy due to mass inertia. Consequently, reducing the weight of the rim is particularly effective.

The ideal material distribution over the width of the rim can be determined using optimization calculations. These show that a reduced sheet metal thickness in the area of the rim flanges and in the drop center impacts negatively on



7 With the same weight, there is no break-even between steel wheels and aluminum wheels

local stiffnesses and stress conditions. A reduction in sheet metal thickness is possible in the rim shoulder area and between the rim shoulder and drop center, ⑥. A maximum weight reduction of 27 % was determined based on the simulation results.

The rim's calculated sheet metal thickness distribution can be implemented using two different technologies: either with Tailored Strips or Tailor Rolled Blanks or with the flow-forming method. In this method, pressure rollers specifically and continuously adapt the rim blank's different areas of thickness. This form of mechanical processing additionally strain hardens the initial material, thus increasing its resulting strength. Flow-forming is already an established process for manufacturing wheels, particularly for truck wheel discs, and is therefore also the method of choice for realizing stress-optimized passenger car rims.

The virtual design and experimental testing of the lightweight wheel were undertaken jointly by ThyssenKrupp and wheel manufacturer Magnetto Wheels. In particular, production of the weight-optimized rim is carried out on the wheel manufacturer's production lines. The prototype wheel disc variants and the rims are joined together using conventional production methods. Fatigue tests under rotary bending loads of 75 % round off development.

LIGHTWEIGHT WHEEL COST AND ENVIRONMENTAL PERFORMANCE

The cost assessment of the developed lightweight wheel is positive. The material savings on the rim fully compensate the additional expense of the flow-forming process. Conversely, the reduced sheet metal thickness of the cold-formed wheel disc is unable to fully compensate the higher material price. The weight saving of up to 1.3 kg is faced with maximum lightweight design costs of € 1.10/kg depending on material.

The hot-formed wheel disc also demonstrates that it is sensible and possible to relocate all hot-forming operations to one tool. The technology-related additional costs of hot-forming can therefore be approximately canceled out by material savings and fewer production steps.

Comparing the environmental performance of the reference wheel and light-

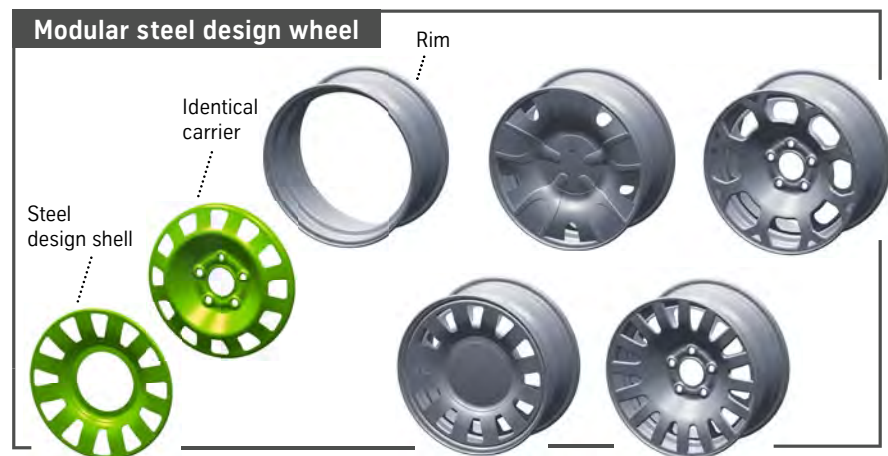
weight steel wheel with representative aluminum wheels reveals particularly interesting results, ⑦. The global warming potential of the different wheel variants is shown over their total useful lives. Due to the high primary energy consumption required to obtain aluminum, more CO₂ is created during the production of aluminum wheels than steel wheels. In addition, the aluminum wheels in the benchmark are considerably heavier than the outlined steel solutions, preventing them from achieving any advantage even during their useful lives. Steel wheels are therefore considerably more eco-friendly and are clearly the better choice, especially for the OEMs' fuel efficiency models. More detailed life cycle analyses for the wheels can be

found in the article entitled "Environmental Performance as an Important Criterion" (see from page 130).

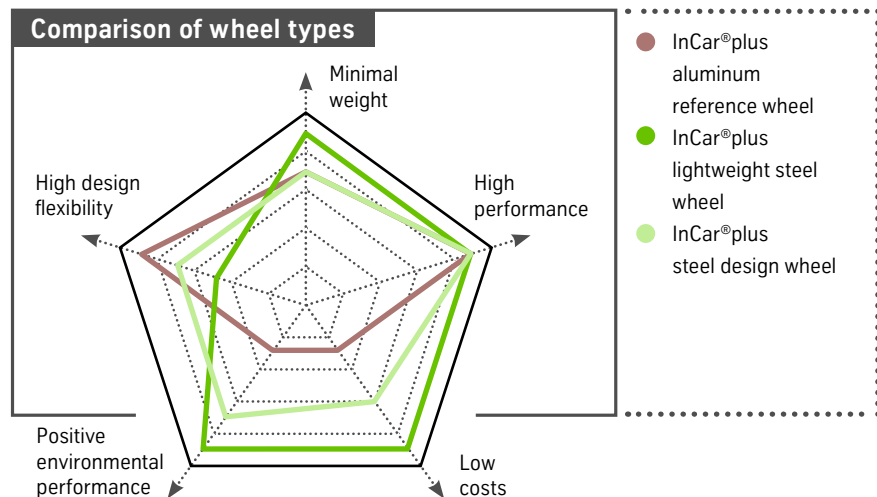
STEEL DESIGN WHEEL CONCEPT DEVELOPMENT

Aluminum wheels are manufactured using the casting method and therefore enable highly diverse designs for comparatively low investment costs. In contrast, the classic steel wheel is characterized by performance, low weight and cost-effectiveness with high unit numbers. ThyssenKrupp combines the advantages of both methods of production in its new steel design wheel, ⑧.

In this modular wheel concept, a basic element bears the majority of the



⑧ Concept for the new steel design wheel



⑨ Comparison of steel wheel innovations and the cast aluminum wheel in the spider diagram

mechanical stress. The wheel obtains its attractive visual appearance from a modular steel design shell, which is connected to and borne by the basic element. This two-part concept offers high design diversity with moderate additional costs with the same weight level as the reference wheel. The modular steel design wheel is actually significantly less expensive than aluminum wheels and its environmental performance is better, 9.

Fiber reinforced plastic covers are usually employed to visually enhance steel wheels. However, these covers cause up to 10 % of the wheel's weight and do not contribute to its structure. The ecological life cycle also deteriorates dramatically due to the plastic cover. Conversely, the reinforcing design shell avoids these disadvantages and offers extensive design scope.

Together with Magnetto Wheels, ThyssenKrupp has verified general manufacturing feasibility and function on two prototype design variants. The prototypes use the lightweight wheel as the basic element and enhance it with two different design shells. The design shell is joined to both the wheel disc and the rim, thus improving stiffness and the flow of force in the wheel. Joining processes include laser beam brazing and classic laser beam welding. Adhesive bonding is also conceivable in the future.

Connecting the design shells in the rim shoulder area causes the wheel to appear significantly larger than a conventional steel wheel joined in the drop center, thus leading to the effect of a semi-full face disc wheel. The concept additionally enables the current trend towards more closed wheel surfaces to be embraced; this is being sped along by the CO₂ debate (improved aerodynamics) and current electric vehicles.

UNUSUAL STEEL-CFRP HYBRID WHEEL

The steel-CFRP hybrid wheel is a high-quality 20-inch wheel for sports cars and the luxury vehicle class; it is competing against forged aluminum wheels in terms of design and weight. The material mix and the innovative joining methods ideally exploit the advantages of the individual materials and lead to the achievement of a visually attractive wheel weighing of just 10.5 kg.

Steel-CFRP hybrid wheel



10 Attractive 20-inch lightweight wheel in multi-material design

The basic idea behind the hybrid wheel is “the ideal material in the right place”. The majority of the wheel's weight is concentrated in the rim with maximum distance away from the rotational axis. A weight reduction is particularly effective here, which is why the new hybrid wheel's rim consists of the lightweight CFRP material. The package in the area of the rim spider is very constricted, whereas the mechanical and thermal stresses and demands on the visual appearance are extremely exacting. Due to these reasons, the ideal material used here must be highly deformable, very stiff, able to withstand high thermal loads and very strong – steel.

To meet the exclusive design requirements of luxury vehicle and sports car buyers, the hybrid wheel is styled very attractively. From numerous drafts, a fine double-spoke design was selected for implementation, 10.

One particular challenge involved in manufacturing metal-CFRP hybrid components is the different thermal expansion coefficients of the individual materials. This challenge is met with special, detailed manufacturing and material technology solutions for the individual components of the steel-CFRP hybrid wheel. This has enabled minimization of the inherent stresses caused in the component due to temperature fluctuations during manufacturing and operation.

The structurally separate shell design used for the rim spider additionally leads to high component stiffness with low weight. For the first time, the outlined concept enabled the achievement of a

20-inch steel-CFRP hybrid wheel with correspondingly high potential savings. Initial trials with the manufactured prototypes are extremely promising. Integration of the assembled steel rim spider or the CFRP rim into further concepts is conceivable.

As part of InCar plus, ThyssenKrupp has virtually reinvented the wheel – and not just one. Optimization of the materials, manufacturing processes and geometries of the steel wheels takes their competitiveness to a whole new level. The new design concepts, in particular, open up wider application areas to the steel wheel thanks to diverse individualization options. The steel-CFRP hybrid wheel's multi-material approach even gives steel access to the segment of high-quality performance wheels with high design standards.

ENVIRONMENTAL PERFORMANCE AS AN IMPORTANT CRITERION

Within the automotive industry, vehicle sustainability is becoming an increasingly important factor in competition. Accordingly, particular value is placed on environmentally friendly materials, manufacturing methods and vehicle components in the InCar plus project. With the help of Life Cycle Assessments (LCAs), the potential environmental impacts of newly developed solutions over the entire life cycle are comprehensively analyzed. There are many solutions that show improvements in all impact categories, as identified by the LCAs.

Over the last several years, not only consumer demands for environmentally friendly products have allowed sustainability to take on a growing relevance; at the political level, more and more regulations concern topics like recycling and ecological product design. In the automotive industry this is predominantly reflected in the EU regulation on reducing emissions, which has required increasingly stringent CO₂ emissions levels for passenger cars and commercial vehicles since 2009 [1]. To date, this has only taken into account the CO₂ emissions produced while driving; however, environmental impacts in connection with production, as well as the recyclability of vehicle components, can also significantly shape a vehicle's environmental performance.

In its life cycle assessments, ThyssenKrupp considers all phases, from the extraction and processing of raw materials, to material and component production, to the end product's use phase and subsequent recycling. **1** The weight reductions made possible by lightweight design produce fewer emissions during the use phase. All lightweight steel concepts mitigate environmental impacts over the entire life cycle; as they require less raw material, fewer emissions are produced in the course of material production. Such is not the case, however, when it comes to materials like aluminum, magnesium and CFRP: though all of them offer great potential for reducing weight, their man-

ufacture often involves high environmental impacts, an aspect which must be compensated for over the course of the product use phase. In the worst case, even the entire use phase does not suffice to compensate for the environmental footprint created during the manufacturing phase – which is why the potential consequences of choosing a specific material or technology should be weighed carefully in advance.

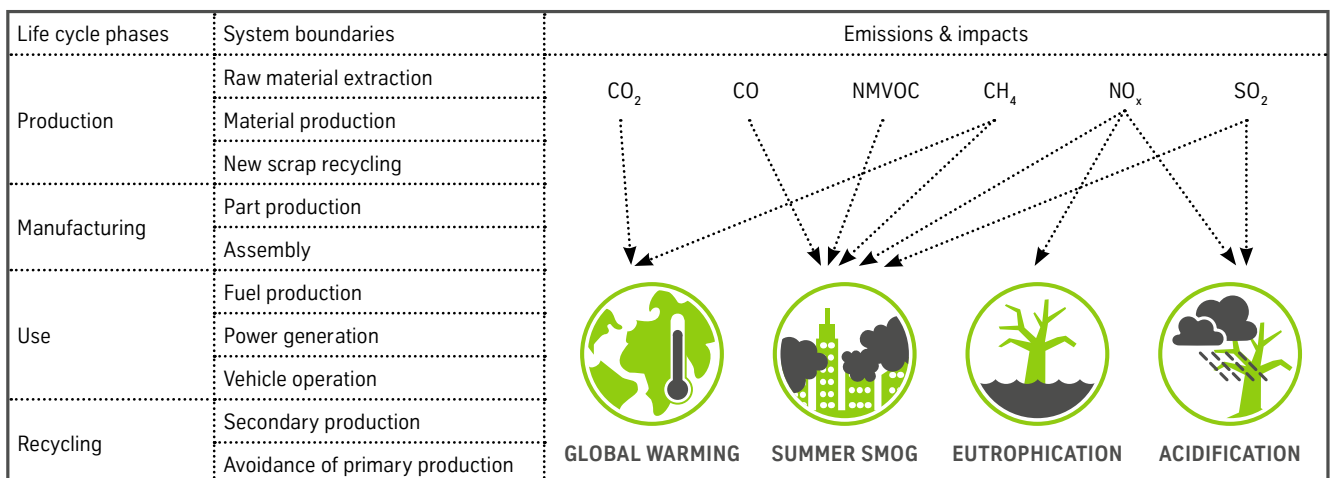
For ThyssenKrupp, taking a comprehensive approach means not only taking into account all phases of the life cycle, but also various environmental indicators; after all, a product with lower life cycle CO₂ emissions is not automatically environmentally friendly. Selecting a new material might reduce the contribution to the greenhouse effect, but simultaneously increase the acidification potential. These trade-offs between different environmental burdens must always be taken into account and critically reassessed. The International Panel on Climate Change's latest report has shed new light on the importance of acidification for our ecosystem [2]; further, resource efficiency has recently been defined as a new focal issue at the EU level [3]. ThyssenKrupp's sense of responsibility for the environment goes well beyond satisfying legal requirements. Accordingly, further impact categories, primary energy demand, typical individual emissions during operation, and resource consumption are included in its life cycle assessments.

RELIABLE BASIS OF DATA AND FLEXIBLE METHODOLOGY

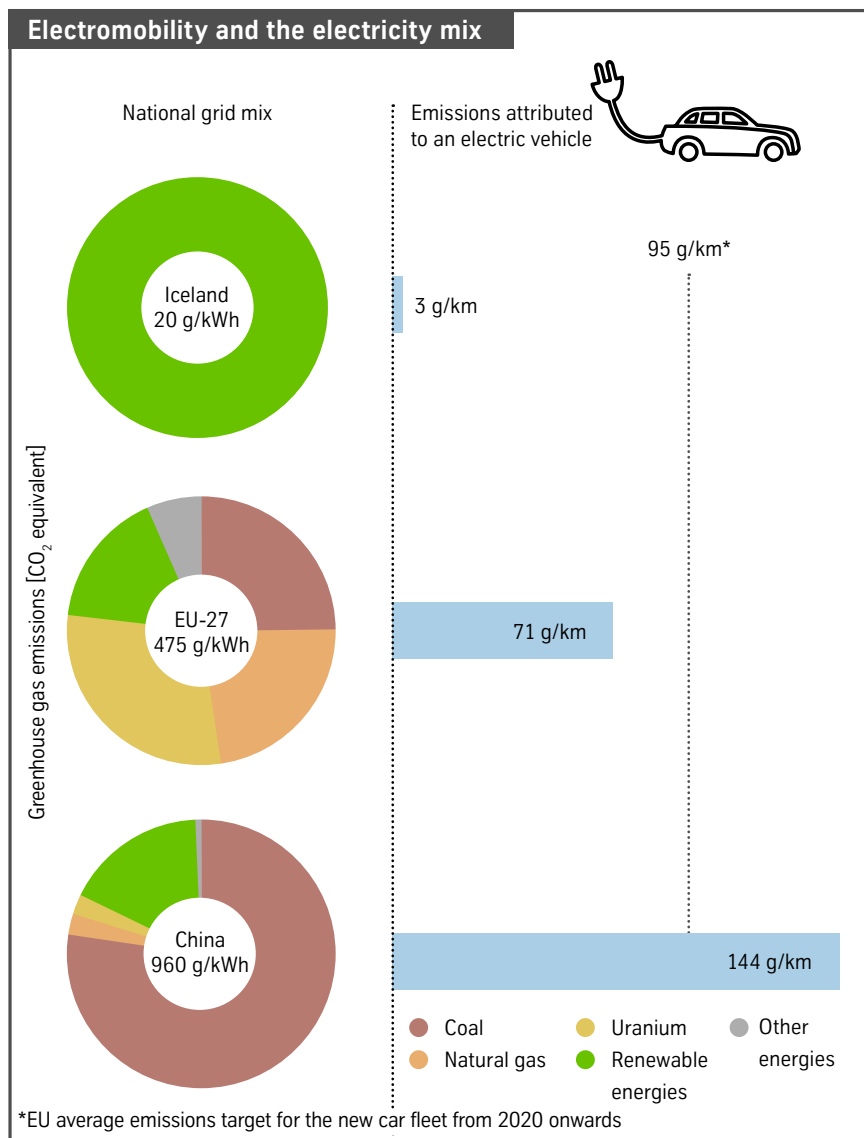
In the life cycle assessment, the manufacturing phase includes all upstream chains for the materials and types of energy used, production of the materials, and the manufacture of the actual component. Useful data on steel production can be found in an internal ThyssenKrupp steel model that shows the environmental impacts of the company's integrated steelmaking facilities and utilizes measurements from 2012. Data sets for other materials like magnesium and aluminum were taken from broadly recognized databases. ThyssenKrupp also collects its own data on the actual manufacture of components.

InCar plus examines a number of different powertrain concepts, an approach that is particularly demanding with regard to modeling the use phase of the product. In conventional vehicles, above all the combustion of fuel is decisive for emissions during this phase; in contrast, in electric vehicles the focus is on the means used to produce electrical power. That being the case, not only direct emissions but also fuel production and electrical power generation are taken into consideration to ensure a consistent representation of the use phase.

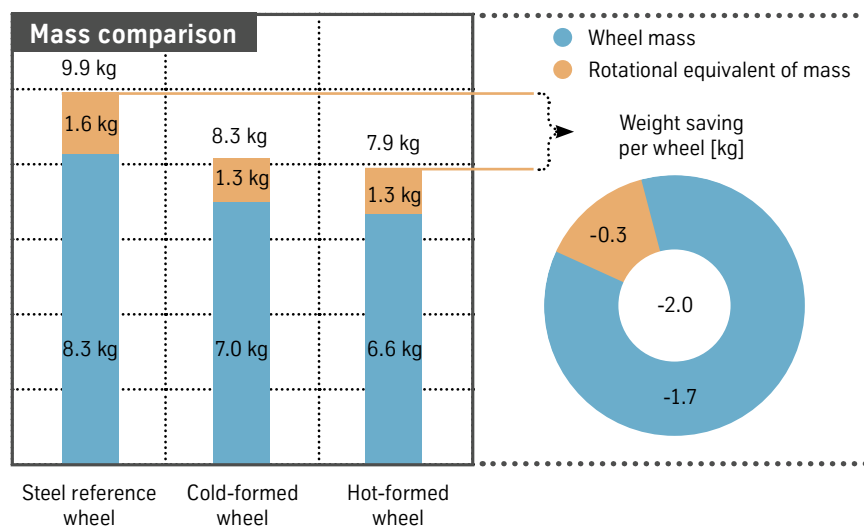
In this regard, the country-specific electricity mix [4] can be of crucial importance to the result, **2**. With a coal-based Chinese electricity mix, an electric vehicle with an energy demand



1 Life cycle phases and impact categories



② Effects of different electricity mixes on the emission attributed to an electric vehicles

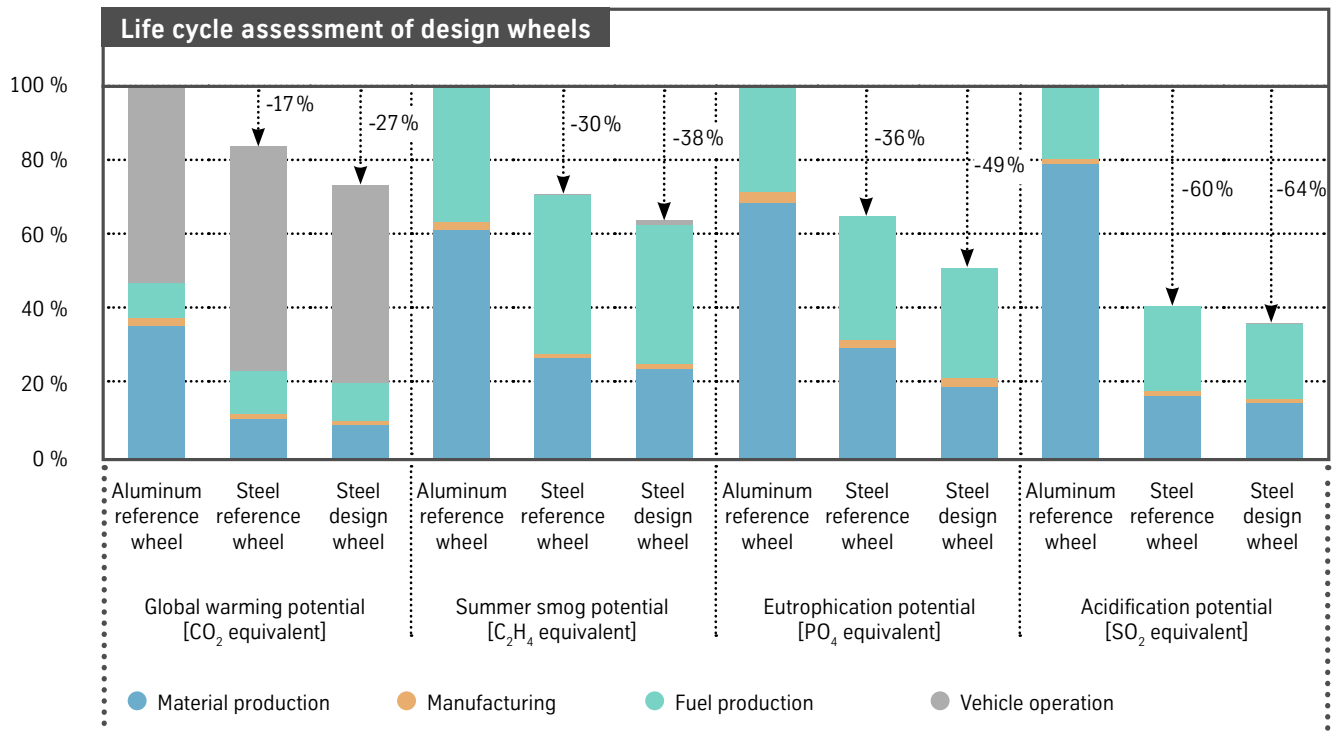


③ Mass and the rotational equivalent of mass of lightweight wheels

of 150 Wh/km produces an average of 144 g CO₂/km – higher emissions than a comparable gasoline engine. In contrast, an electric vehicle powered by renewable energy from Iceland causes only 3 g CO₂/km. As the share of renewable energy in the electricity mix continues to grow, the use phase of electric vehicles will become less relevant and practically emissions-free. This will in turn make the manufacturing phase all the more important, a further context in which the electricity mix plays an important part. Above all, energy-intensive manufacturing steps can be essential to the overall assessment. As such, certain OEMs are now shifting their more energy-intensive production processes to countries with higher percentages of renewable energies. In the context of InCar plus the electricity mix for the German national grid was used, unless otherwise stated.

Estimating the effects of lightweight design on power consumption can pose a challenge in connection with modeling the use phase of electric vehicles. In this regard a number of factors, such as the driving cycle, required range, braking energy recuperation and tire friction are taken into account. With 100 kg less weight, the designated conditions yield energy savings of 6.5 Wh/km.

With regard to conserving natural resources, steel components are characterized by their high recyclability. Given its ferrous properties, scrap steel can be readily separated from other types of scrap. Further, as primary steel and recycled steel display identical technical characteristics, recycling can greatly reduce the consumption of primary raw materials and the corresponding environmental impacts in connection with material production. To account for this benefit, credits are awarded in the life cycle assessments. However, it must be kept in mind that the choice of end-of-life allocation method (in other words, recycling credits) can have a significant impact on materials selection decisions, [5]. In the basic scenario, full credit is awarded for the scrap recycling taking place today, e.g. for scraps of metal sheets at press shops. In this case, complete substitution of primary production is assumed, minus the recycling effort involved in e.g. melting the scrap in an electric furnace. No credit will be awarded for future end-of-life vehicle



4 Ecological life cycle assessment of the steel design wheels in comparison with the aluminum and steel reference wheels

scrap in the basic scenario. However, a recycling potential that yields improvements on the basis of end-of-life recycling is shown for all concepts. ThyssenKrupp consistently adheres to the ecological life cycle standards ISO 14040/44

for research purposes; the

conformity to said standards is certified by an independent auditor and documented in an extensive report. Comprehensive assessment software (GaBi 6) is used for modeling. The primary goal of the LCA studies is to arrive at an objective and accurate evaluation of the new concepts. The scope of research is consistently selected in such manner as to guarantee that the products offer the same functionality and are thus mutually comparable; the defined parameters are also realistic and representative. To meet the specific life cycle assessment requirements of the automotive industry, the models are structured so that different parameters, such as the electricity mix, fuel-weight elasticity, and the handling of recycling credits

can be varied. In the following, these life cycle assessments are described on the basis of selected examples.

CONSUMPTION-OPTIMIZED STEEL WHEELS

The development of steel wheels employs two different approaches with a common objective. Either by means of lightweight design or solely of design, more competitive steel wheels are to be achieved. The InCarplus steel wheels display considerable ecological advantages over cast aluminum wheels – beginning with lower environmental impacts during manufacturing and continuing throughout their use phase and subsequent recycling.

The use phase of the wheels is calculated on the basis of a mid-size vehicle with fuel consumption of 6.2 l/100 km and fuel-weight elasticity of 0.35 l/100 km/100 kg [6], and which is driven a total of 200,000 km. Since the wheels are rotating masses, the lower weight due to lightweight design serves to further reduce consumption (see article “New Wheels Made of Steel – Light and Stylish” from page 124). Above all, this aspect depends on the speed profile and the wheel’s moment of inertia. A

consumption simulation is used to determine the influence of rotating masses on the basis of the New European Driving Cycle (NEDC).

The lightweight wheels with flow-formed rim band and optimized wheel disc are even lighter than the best-in-class steel reference wheel from the benchmark. Consequently, the environmental impact of wheel solutions with a hot-formed wheel disc (HF) is 23 % lower, while that of solutions with a cold-formed wheel disc (CF) is 18 % lower.

Despite the greater amount of energy involved in hot-forming, lightweight design makes it possible to reduce material use to such an extent that the improved life cycle assessment is already clearly recognizable at the end of the manufacturing process. The positive effects of the lower rotating masses on fuel economy ensure particularly high environmental advantages during the wheels’ use phase. 3 shows the percentage of mass subject to translatory (blue) and rotational (orange) motion in the wheels. In addition to the reduction in weight, the HF wheel with a moment of inertia of 0.2 kg/m² also delivers 18 % (0.3 kg) less rotational equivalent of



mass: this rotational effect is even more pronounced if a dynamic driving style is employed. The life cycle assessment reveals extensive environmental advantages, from raw material extraction to recycling, for both the hot-formed and cold-formed wheels.

DESIGN WHEELS: SAVING FUEL ELEGANTLY

Aesthetics are a crucial purchasing criterion for design wheels. InCar plus design wheels made of dual-phase steel offer innovative styling as aluminum wheels. The weight of aluminum wheels varies greatly depending on their styling. The benchmark shows that aluminum wheels with the same dimensions and load capacity weigh at least as much, and in some cases even 30 % more than steel wheels. The best-in-class aluminum wheel with a weight of 8 kg and a conventional steel wheel covered by a 600-g glass fiber reinforced polyamide hubcap were selected as reference wheels for the purpose of comparison. In contrast, the InCar plus design wheel is made exclusively of steel.

The steel design wheel's lower environmental impacts throughout the entire life cycle are primarily due to the material production, ④. During manufacturing, steel requires significantly less energy, water and other resources and therefore produces far fewer emissions

than aluminum. A further advantage is that, unlike with the reference steel wheel, there is no need for a plastic hubcap.

In fact, the environmental impacts of aluminum production are so high that they can no longer be compensated for during the use phase of the wheel. This clearly shows the importance of pursuing a comprehensive approach that takes into account the manufacturing process and other impact categories, in addition to the potential for exacerbating global warming. The comparatively environmentally friendly methods used in steel production lead to obvious improvements in all environmental categories.

Compared to other body components, wheels are easier to remove at the end of their use phase, which should theoretically yield a higher recycling rate. If we assume 100 % recyclability for both steel and aluminum, together with full recognition of credits, the aluminum wheel offers a potential 26 % reduction in greenhouse gas emissions, ⑤. The amount of the credit reflects the fact that melting aluminum scrap takes far less energy than producing primary aluminum.

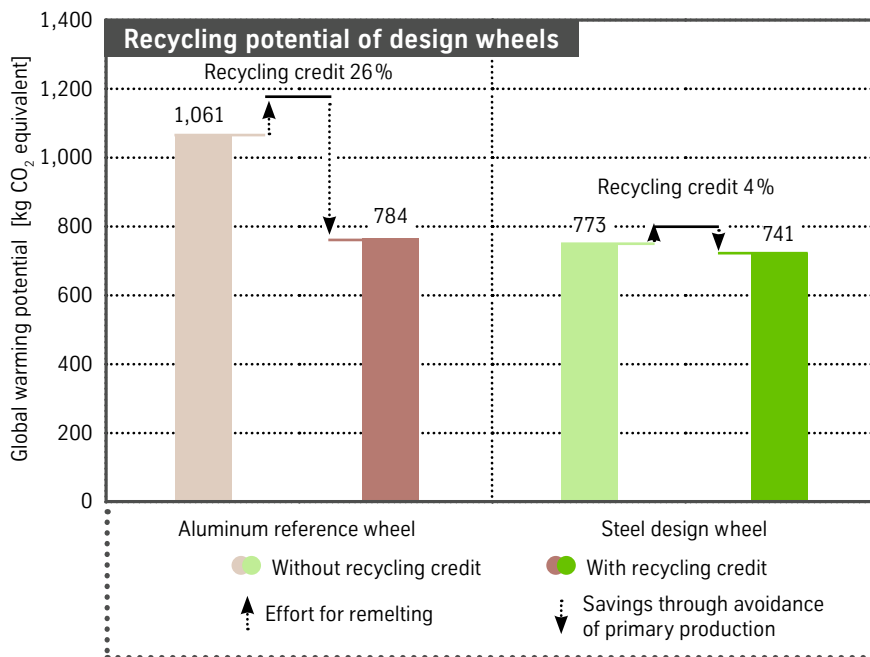
Though the complete recycling of steel wheels only cuts their greenhouse gas emissions by 4 %, if the credits for steel and aluminum are recognized in full, they still outperform the aluminum wheels in all environmental categories.

As such, a comprehensive evaluation shows that InCar plus design wheels offer improvements with regard to all life cycle phases, impact categories and primary energy requirements.

OPTIMIZED ROTOR FOR ELECTRIC MOTORS

Electrification of the powertrain is a primary means of reducing CO₂ emissions in automobiles. However, electric vehicles are still at the beginning of their technical evolution; their range, battery life, safety and costs still need to be optimized. In electric vehicles, lightweight design is an essential parameter with regard to reducing energy requirements throughout their use phase. As previously explained in ②, the electricity mix used is crucial to CO₂ emissions and all other environmental impacts, and therefore to a vehicle's environmental footprint. Lower energy consumption is important not so much with regard to regulations on CO₂ but because of its effect on range and battery capacity.

As part of InCar plus, ThyssenKrupp is also developing solutions for improved electric mobility. One highlight is a hollow cylindrical rotor that weighs roughly 2.2 kg (18 %) less than its conventional counterparts. The reference rotor is made of a solid steel shaft and pressed-on laminated core. Thanks to innovative manufacturing techniques, the multi-part



⑤ End-of-life recycling potential for the aluminum reference wheel and the steel design wheel

InCar plus rotor can be cost-attractively produced. It consists of a middle tube section that attaches to the laminated core, as well as corresponding end sections for installation and force output. Different grades of steel can be used for the individual sections. For the purpose of the life cycle assessment the magnets were disregarded, as they are identical in both rotors.

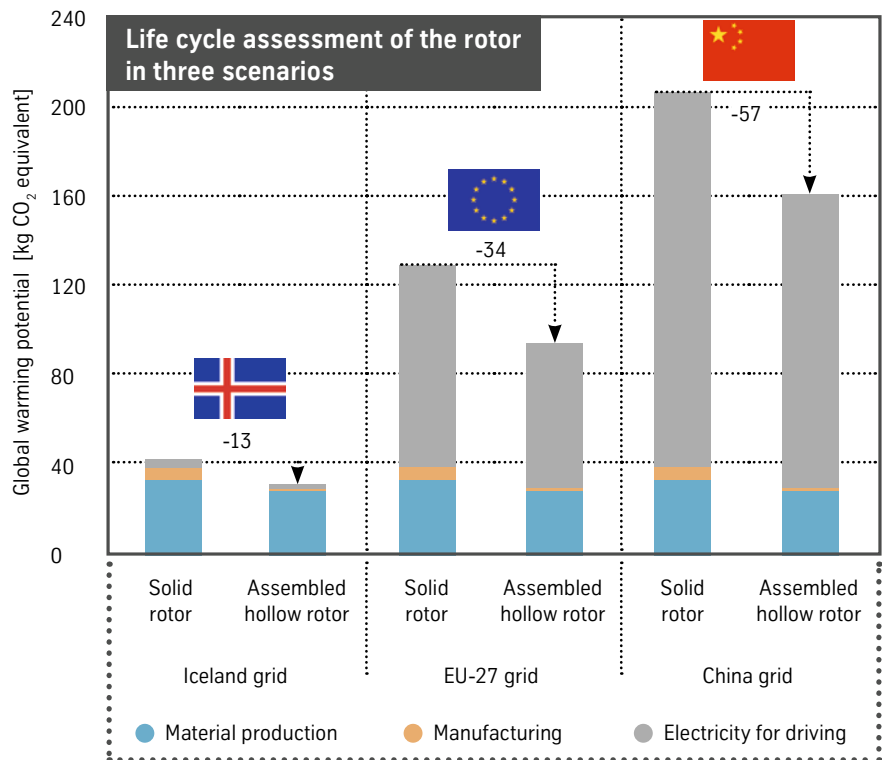
Since both variants are made of steel, the results for the manufacturing phase are proportional to the mass. Due to the increased amount of cuttings produced by lathing the shaft, the environmental impacts of manufacturing the components are higher in the reference rotor.

The use phase of a small electric vehicle is defined as 150,000 km and greatly depends on the choice of electricity mix used. In the context of the study, a sensitivity analysis using the EU electricity mix as a basis was performed for the Chinese and Icelandic electricity mixes, too.

If we examine the reference case with the European electricity mix, the assembled rotor produces approximately 34 kg less CO₂ equivalent than a conventional solid rotor over its entire life cycle. 12 kg less are produced in its manufacture; the remainder is due to the lower energy consumption, thanks to the rotor's lower mass and moment of inertia.

⑥ shows the extent to which the results for the use phase depend on the electricity mix used. With the Icelandic electricity mix, the potential environmental impacts only decline slightly during the use phase. Accordingly, the product's ecological characteristics can primarily be improved in the manufacturing process. In this case, the assembled rotor produces roughly 13 kg less CO₂ equivalent. The Chinese electricity mix is then presented as the other extreme. Given the high percentage of coal used to generate electricity, the emissions in China are considerably higher than in the EU electricity mix. As such, if used in China the assembled rotor would cause roughly 57 kg less CO₂ equivalent in terms of greenhouse gases.

The ability to which the potential for global warming can be reduced is therefore highly dependent on the target market's energy mix. With the help of lightweight design and an efficient powertrain, emissions can be effectively reduced during the use phase. In turn, choosing the right material and technol-

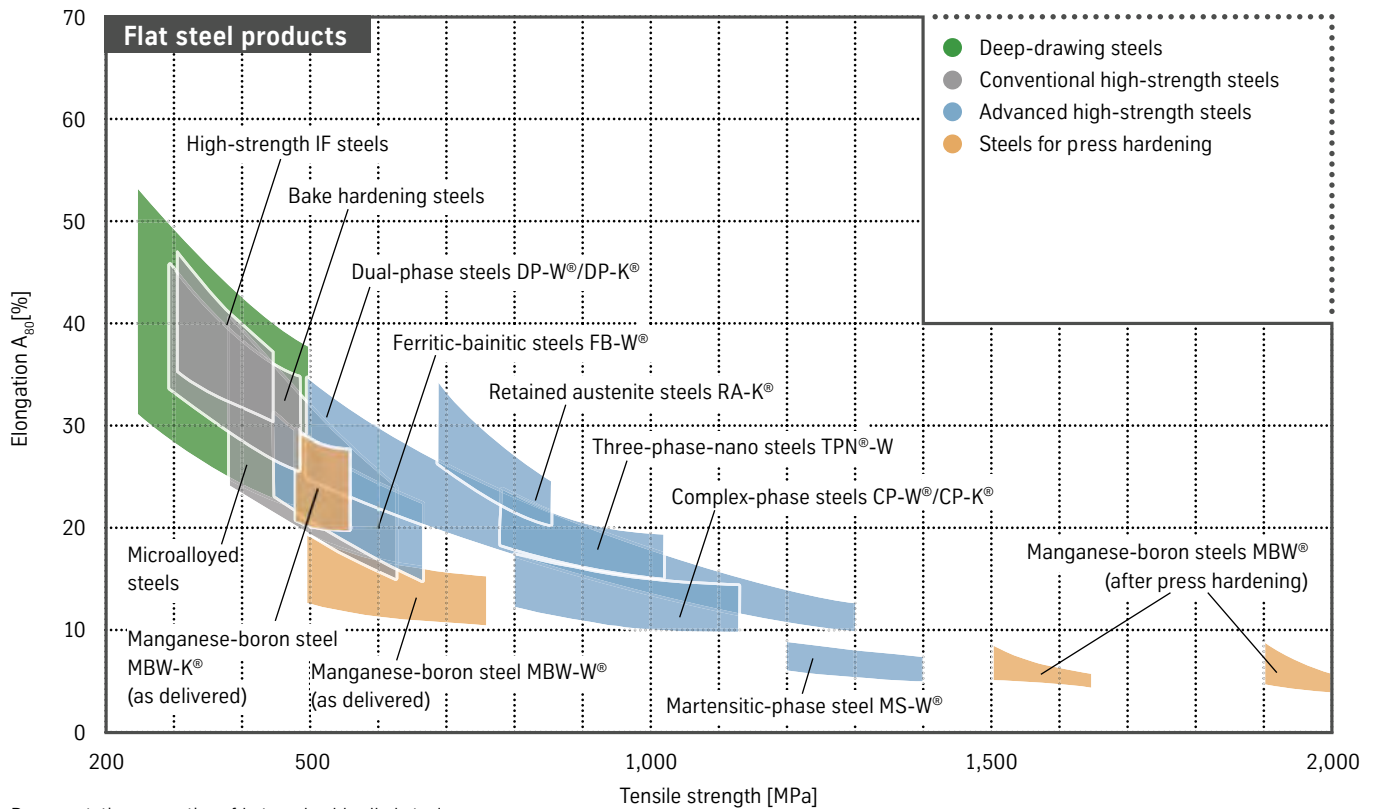


⑥ Ecological life cycle assessment of the solid rotor and assembled hollow rotor

ogy is crucial to achieving resource-saving, low-emissions manufacturing. As an environmentally aware automotive supplier, ThyssenKrupp is developing InCar plus solutions to actively contribute to sustainable mobility.

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SCALUR

The Scalur product family encompasses hot-rolled deep drawing and complex phase steels as well as microalloyed grades with particularly tight tolerances and low thickness as of 1.20 mm – characteristics previously reserved for cold-rolled material. The Scalur steels are additionally characterized by their low trace element content and good sulfide purity.

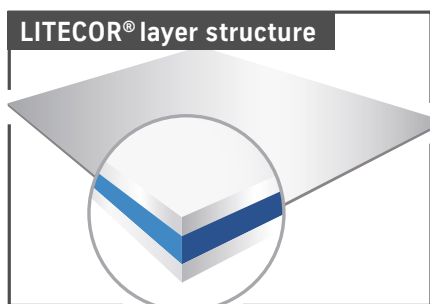
LITECOR

Litecor is a flexurally stiff and buckling-resistant steel-polymer composite for

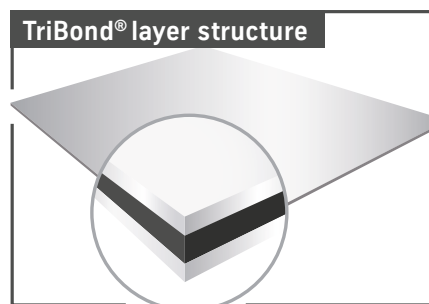
lightweight design of planar inner and outer panel components which combines the strength of steel with the low weight of plastic. To achieve this, a comparatively thick polymer core layer is firmly bonded with two steel cover sheets which are only around 0.2 to 0.3 mm thick. Depending on the intended application, this enables the weight of planar components to be reduced by up to one third. Litecor can be formed similarly to monolithic steel sheets and can be spot welded in a modified process. The steel-polymer composite can also be hemmed and cataphoretically painted.

TRIBOND

TriBond is a family of three-layer steel composites for hot-forming – designed primarily for crash-relevant structural components. The material's special characteristics are its high energy absorption and high possible bending angles. These properties are achieved by combining ultra high-strength with highly ductile steels in a steel sandwich material with extensive lightweight design potential. Its processing behavior is similar to that of monolithic steel sheets and requires no process adaptations in component manufacturing.



Steel sheet 0.2 to 0.3 mm
Polymer core layer from approx. 0.3 mm
Steel sheet 0.2 to 0.3 mm



Ductile steel 10 to 20 %
Ultra high-strength steel, 60 to 80 % of total thickness
Ductile steel 10 to 20 %

THYSSENKRUPP STEEL EUROPE DESIGNATION	DIN EN	VDA 239-100	USA (ASTM)	JAPAN JFS A
CR210IF	HC220Y, HX220YD	CR210IF	—	JAC390P
CR210BH	HC220B, HX220BD	CR210BH	—	JAC340H
CR240LA	HC260LA, HX260LAD	CR240LA	—	JSC440W
CR300LA	HC340LA, HX340LAD	CR300LA	HSLA Grade 50	JAC440R
CR380LA	HC420LA, HX420LAD	CR380LA	HSLA Grade 60	—
CR420LA	HC460LA, HX460LAD	CR420LA	HSLA Grade 65	—
HR420MC	S420MC	HR420MC	HSLAS-F Grade 60 Class 2	—
MHZ 500	HC500LA, HX500LAD	—	HSLA Grade 70	—
SCALUR® S550MC	S550MC	—	—	—
HSM700HD	—	—	—	—
DP-W® 330Y580T	HDT580X	HR330Y580T-DP	DP590/300Y	JSH590Y
DP-K® 290Y490T	HCT500X	CR290Y490T-DP	DP490T/290Y	—
DP-K® 330Y590T	HCT600X	CR330Y590T-DP	DP590T/340Y	JSC590Y
DP-K® 440Y780T	HCT780X	CR440Y780T-DP	DP780T/420Y	JSC780Y
DP-K® 590Y980T	HCT980X	CR590Y980T-DP	DP980T/550Y	JSC980Y
DP-K® 700Y980T	HCT980X-HY	CR700Y980T-DP	—	—
DP-K® 780Y1180T	—	—	—	—
CP-W® 660Y760T	HDT780C	HR660Y760T-CP	CP780T/620Y	—
CP-K® 570Y780T	HCT780C	CR570Y780T-CP	—	—
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TPN®-W 700Y870T	—	—	—	—
RA-K® 400Y690T	HCT690T	CR400Y690T-TR	TRIP690T/400Y	—
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