DEUTSCHE
MASSIVUMFORMUNG

Lightweight Forging

Potential of Forged Components

Info EXTRA

Foreword

The demands placed on all technologies of automotive manufacture are clearly defined by the legislative authority. Strict EU emission requirements are prompting manufacturers to more than double the share of lightweight components in their vehicles over the next two decades.

This is a goal that is especially directed at suppliers to the industry. Due to their particular strengths, forging companies in Germany have been an important innovative partner to automotive manufacturers for decades. These strengths lie in the development and production of highly stressed parts as well as in exhausting all the possibilities offered by materials to find the optimum one for the particular process. Mainly these materials are steels.

Faced with this challenge and given the pioneering results of several lightweight design projects between 1994 and 2002 which primarily focussed on the area of the vehicle body, The Lightweight Forging Initiative was created in February 2013. Nine companies from the steel industry as manufacturers of wire and bar joined forces with 15 forging companies under the auspices of the German Forging Association (Industrieverband Massivumformung e. V.) to form the Initiative. This cross-company and cross-sector consortium brings together know-how from materials science and forging technology, allowing the participating companies to transfer the insights they gain into the parts supplied to the automotive industry.

In an initial study carried out during three workshops, the potential of forget parts for generating weight savings was demonstrated on a middle-class vehicle. The analysis focused in particular on the powertrain and chassis. The 400 ideas derived from this then underwent a feasibility check.

This EXTRA-Info will report on the motivational factors of this pre-competitive consortium and will primarily focus on the procedure and the results obtained from the joint research into automotive weight-savings potential. As know-how from the areas of steel manufacture and processing were brought together in the Initiative, optimization proposals could be examined from all angles.

Based on the lightweight design potential which has already come to light, it would make sense to continue the analyses and to extend them to encompass other vehicle classes. At the same time, the results reveal that there is a considerable need for research. This requirement has already been addressed with the submission of a comprehensive research proposal.

With this latest issue of our EXTRA-Info series, we are pleased to provide effective support on all issues of modern, innovative products and processes to all those interested and involved in the development of "Lightweight Design with Forging". We hope this publication will be used actively and find diverse application.

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Introduction

"Lightweight Forging" – at first, this appears to be a paradox. After all, in contrast to sheet-metal forming, forging is a "bulk" or "massive" metal forming process, where the starting material is in the form of billet, rod or slab. The terms "bulk" and "massive" are generally associated with synonyms such as "solid" and "dense" in contrast to "hollow", and thus imply "heavy" or "weighty". The meaningfulness of the description "Lightweight Forging" becomes clear, however, if technically more appropriate synonyms such as "strong", "durable" and "resilient" are used or other more common terms such as "tough" and "effective".

"Lightweight forging" represents the strive towards designing mobility technology in a sustainable and lasting way and expresses the goal of finding a technical solution with minimum mass utilization.

This is particularly important if these masses need to be driven, i.e. when the task of technical components is to achieve mobility. Human physical strength for driving mobile technical devices is so limited that motorized drives need to be employed in almost all cases. On the one hand, this renders the burning of fossil fuels necessary for energy provision or generation. On the other hand, it leads to the emission of greenhouse gases into the environment.

It was from mankind's high demand for mobility that automotive technology emerged more than 100 years ago. The automotive industry relies on steel manufacturers for high-quality materials and on forging companies, with their numerous and diverse processes, for important parts and components. Effective lightweight design achieved through "massive" forming, i.e. forging, has thus arisen from a megatrend of automotive engineering.

1.1 Trends and Driving Forces for Automotive Lightweight Design

Since the beginning of car mobility, the strive towards individual motorized travel among the global population has grown inversely proportional to the earth's resources of the fossil fuels required for this. At the same time, the increasing demands placed on vehicles with respect to comfort and safety have given rise to significantly higher overall vehicle weights.

Particularly worthy of mention in this context is the improvement of driving dynamics through continuously optimized braking and accelerating properties, as well

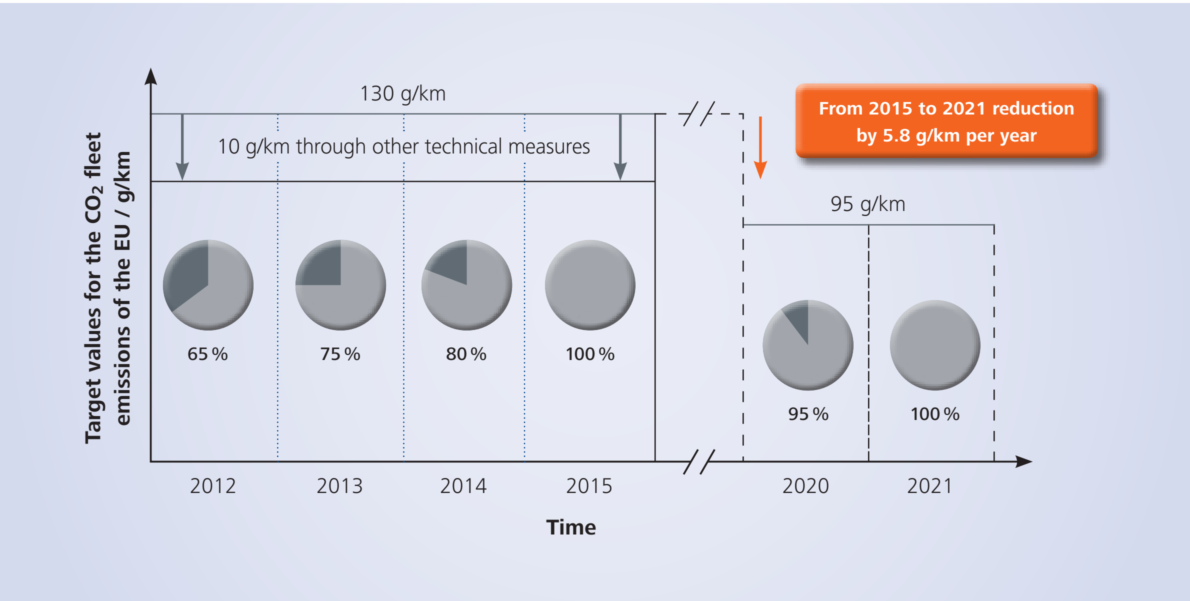


Figure 1: CO_2 targets for European new car fleet from 2012 to 2021

as the reduction of purchasing and operating costs [1]. Furthermore, secondary lightweight design potential is being addressed, which can be scaled through reduced vehicle mass. This affects the areas of the drive, brakes and suspension (i. e. chassis) and amounts to 30 % of the primary potential.

However, it is ultimately the legislative authority which is formulating an ambitious challenge. What is being referred to here is the European Union legislation regarding the reduction of CO_2 emissions, in particular the regulation for reducing CO_2 emissions in cars, which came into force in 2009. Under this regulation, automotive manufacturers are obliged to limit the emission values of all new vehicles to a threshold value of 130 g/km by 2015 and to 95 g/km by 2021. The phase-in values which are valid prior to 2015 are shown in Figure 1 [2].

The technical measures leading to lower consumption and thus to a reduction in emission volumes are numerous. Forged components can support engineering developments here in the areas of combustion engine, transmission and, above all, lightweight design, thereby contributing to desired technical advancements [3]. In other words, forging companies already hold the answers to these megatrends.

1.2 Motivation for The Lightweight Forging Initiative

The graphical representation of the "Weight Spiral" (Figure. 2) illustrates the necessity for switching from an upward to a downward movement, and is explained in more detail in [4].

The left side of the graph reveals the situation over the past decades: Increasing demands placed on the parameters shown led to an increase in weight of the car body. As a result, the chassis, powertrain and also components such as the tank were strengthened or enlarged. This in turn meant that the car body needed to be modified, and so manufacturers became caught up in the spiral.

The break in this spiral only succeeded with the use of lightweight design potential in the car body. This solution approach from vehicle manufacturers shown on the right half of the graph opens up scope for suppliers focussing on the powertrain and chassis.

Accordingly, automotive lightweight design has concentrated very much on sheet-metal forming and the car body to date. This may be seen from the most important major lightweight design projects from various initiators (steel industry, individual steel manufacturers

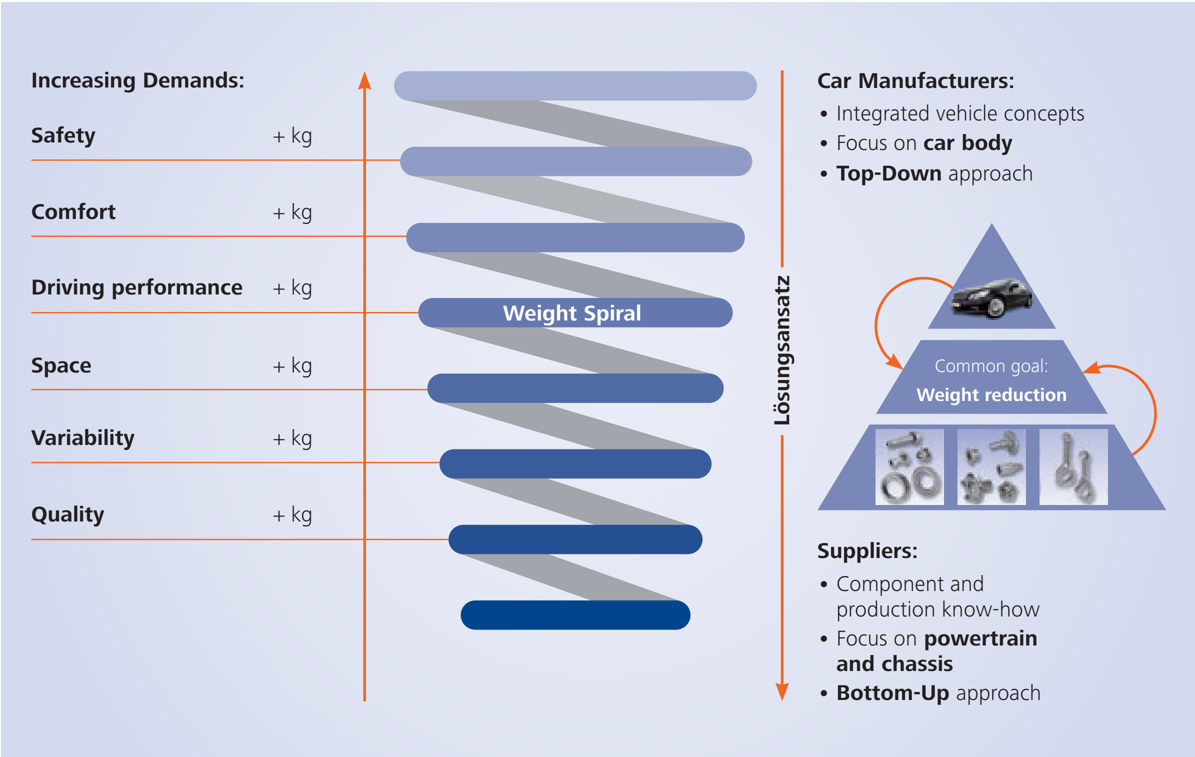


Figure 2: Reversal of the Weight Spiral through lightweight design in the powertrain und chassis

or suppliers, OEMs) which are summarized in a chronological overview in Figure 3.

It is evident that the current potential of the car body as the largest constituent element of vehicle weight has been largely tapped using modern material and processing concepts. Instead, attention is now turning to the powertrain and chassis, which together make up an average of 41 % of the vehicle weight [5].

A considerable motivating factor in forming the indus-try initiative comprising steel manufacturers and forging companies was thus given: The Lightweight Forging Initiative [6] was created at the beginning of 2013, bringing together 15 forging companies and 9 steel manufacturers under the auspices of the German Forging Association and the Steel Institute VDEh. Without drawing on public funding, this consortium is financing the study "Lightweight Design Potential of Forged Components in Passenger Cars", which is outlined in more detail in Chapter 2. The goal of the study is to optimize forged steel components in the car with respect to lightweight design. The Lightweight Forging Initiative is by far the largest pre-competitive joint project of these two industries to date.

The idea originated back in 2011 based on the conviction that individual companies certainly cannot achieve the broad level of ingenuity and creativity that is possible as part of a cooperation. Many automotive manufacturers seemed to be interested primarily in recent manufacturing processes and technologies, paying little attention to the development of proven processes. The Lightweight Forging Initiative, as a cross-sector project, brings together concentrated know-how from materials science and forging technology – and this was to be the decisive multiplier. From the viewpoint of the steel manufacturers, it seemed highly important to allow advancing materials development to flow into end products. In this way, the automotive industry would optimally exploit modern high-strength steels and be able to generate new application possibilities which fulfil economic and ecological considerations [7]. By pooling competence and know-how, an integrated optimization approach is possible, ranging from steel composition to the production of ready-for-assembly components.

The Lightweight Forging Initiative was created to highlight to the professional world the contributions which forging makes to the automotive megatrend of lightweight design. Furthermore, through timely and targe-

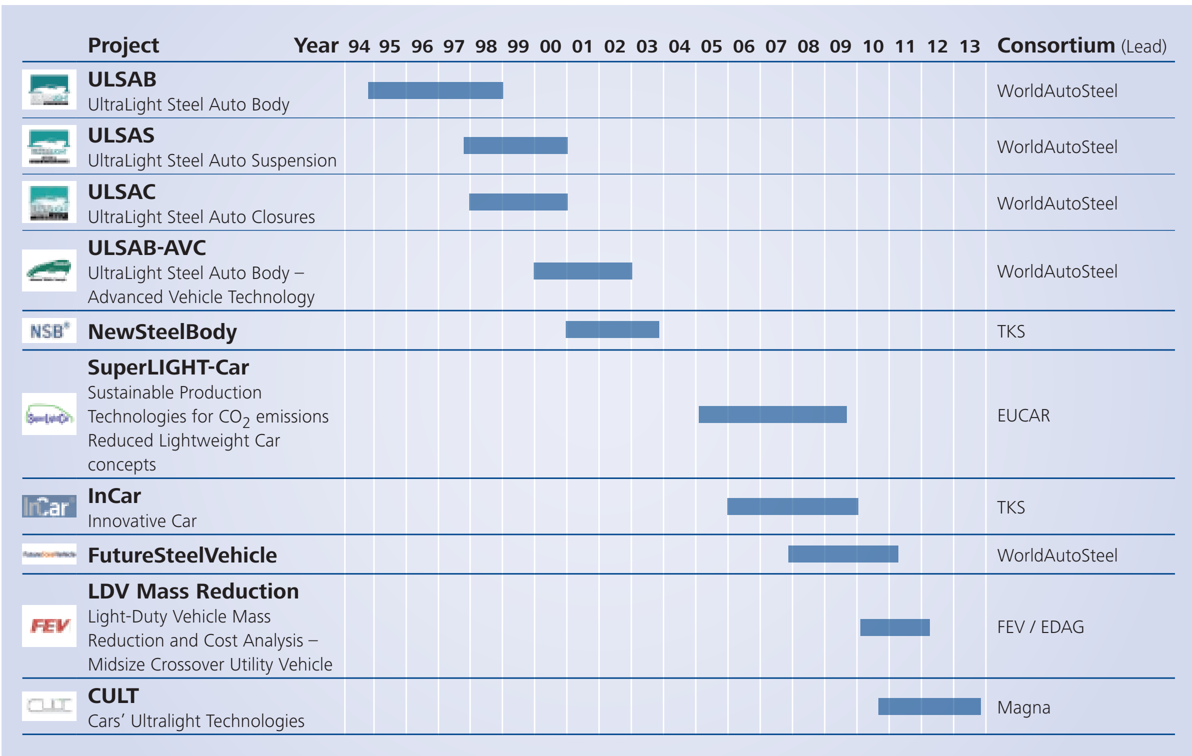


Figure 3: Overview of some important lightweight projects in the automotive environment (1994 to 2013)

Figure 4: Logo of The Lightweight Forging Initiative

ted dialogue between steel and component suppliers on the one hand and automotive customers on the other, the potential should be incorporated at the early stages of system and part development. At the same time, it is important to use proven methods of simultaneous engineering to initiate new solution approaches from conceptual lightweight design.

1.3 Selection of Lightweight Design Innovations in Forging

The possibilities and physical-technological correlations in the various disciplines of lightweight design through forging, which may be subdivided into the areas of material lightweight design potential (material requirements), lightweight potential through structural design (topology and design optimization) and lightweight design potential through manufacturing measures (fibre flow, surface treatment processes), are described in detail in [8] and [9], among others. For this reason, the following will present a selection of innovative solutions without any claim to completeness, offering a basic overview of lightweight design solutions already implemented in series.

In the area of material lightweight design in the chassis, substituting steel components with parts made of aluminium is already a well established approach. An example of this is the car rear-axle wheel carrier shown in Figure 5, which underwent significant reworking as part of a change in model. Through improved design as an aluminium forging as well as a modified bearing generation, the system weight was reduced by 1.8 kg. Although part of this weight reduction is thus not attributable to the change in material, the potential of forging is nevertheless clear [10].

Aluminium forged parts are also used in other applications besides cars. Through optimizations with respect to design and requirements, they also find application in motorcycles, as the trailing link in Figure 6 shows [11]. It was thought in the past that the filigree design of this part could not be produced by means of forging.

It is clear from the above-mentioned examples that the geometry and the assembly space of a component likewise play a decisive role. Experience also shows that apparently simple tasks in the area of material lightweight design very often require comprehensive design modifications. In such cases, it becomes clear that substituting materials in favour of "lighter" ones is not more effective than retaining the existing material group and perfecting part geometry through structural design or optimizing the manufacturing process [12].

This insight leads both to design and production solutions in forging, such as hollow shafts. Particularly in

Figure 5: Car rear-axle wheel carrier – left: steel, right: next generation made of aluminium with reduced system weight

Figure 6: Motorcycle trailing link as an aluminium forging

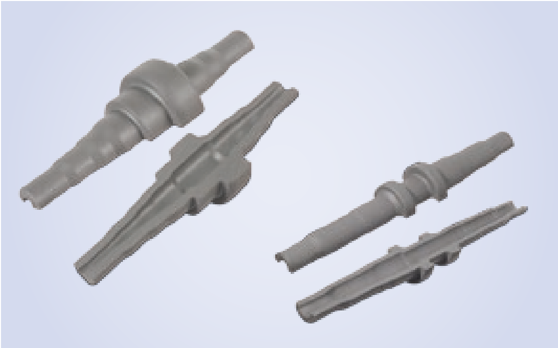


Figure 7: Forgings for hollow transmission shafts, left 27 % and right 38 % weight reduction

Figure 8: Examples of hollow swaged steering shafts

the area of transmissions, hollow shafts are gaining in importance. This is due to technical necessity, such as in double-clutch transmissions, or in some electrical drive concepts. Furthermore, a hollow transmission shaft has the required lightweight design potential, as the necessary torsional stiffness, among other things, is barely affected by the core of the shaft. These savings can thus be achieved here by reducing non-load-bearing cross sections. Figure 7 shows hollow shaft forgings for transmission shafts. These were produced by means of a multiple-stage cold forging process combined with machining. The weight savings amount to 27 % and 38 % [10], [13].

In view of the diverse forging production technologies, several other hollow lightweight shafts are possible using the processes of swaging and extrusion. The application area ranges from hollow steering shafts (Figure 8) to hollow transmission and input shafts as well as shock absorber elements. With this production technology, extremely high surface qualities can be generated, often rendering subsequent machining operations unnecessary. This is achieved through incremental forging with a very high stroke frequency at very low deformation per stroke. The high level of strain that is possible with swaging allows great design diversity. With forward extrusion, stable and precision-quality splines can be produced, which are often also required on a shaft [14].

There are two other established principles for lightweight design in forging which are worthy of mention: functional integration and the assembled component. An example of the functional integration of parts that were previously forged separately is a truck steering knuckle and the associated wishbone, which are merged into an integral forging following thorough FE analysis [15].

The opposite route may be taken by an assembled camshaft, for example. Here, instead of forging the raw part in one piece as is customary, the actual shaft is designed as tubing and the cams are produced separately as a forged part. In this case, the most cost-efficient form of production is on fully automatic horizontal multistage presses, which generate the cams with a rapid cycle frequency at consistently high quality.

With this wealth of experience and the potential it holds, the participants of The Lightweight Forging Initiative entered their first major project phase with a study on lightweight design potential. The results of this will be presented in the next chapter.

Lightweight Design Potential of Forged Components in Passenger Cars

2.1 Conducting the Study on Lightweight Design Potential

2.1.1 Procedure and Steps

During an initial step, The Lightweight Forging Initiative conducted a study on lightweight design potential, which took the form of several workshops between February and October 2013. The basis of these workshops was a methodical approach consisting of five successive working points. The project activities are shown in Figure 9.

Firstly, a systematic overview of lightweight design potential was generated for the powertrain and chassis of a passenger car. This was based on research results and projects from this area published to date as well as on an analysis of accepted lightweight design costs per vehicle.

Following this, the second step involved benchmarking. Here, a car with only low mileage was procured as a reference vehicle and systematically disassembled by the automotive engineering institute, fka Forschungsgesellschaft Kraftfahrwesen mbH Aachen, which was commissioned to carry out the study. The reference vehicle selected was a middle class estate car from a German manufacturer with significant series volume, a diesel engine with double-clutch transmission as well as all-wheel drive. During disassembly of the entire vehicle, parts were classified according to the decisive categories of the study, namely the powertrain, i. e. engine and transmission, as well as the chassis and other components.

All assemblies and individual parts were analysed, with parameters relating to dimension, material and of course weight being stored in an online database. To determine the material, analysis was also carried out in the materials laboratory, where necessary. Furthermore, another important aid was comprehensive photo documentation, which is complemented by assembly drawings from the manufacturer.

Three facilitated hands-on workshops on the vehicle areas of powertrain, chassis and other components formed the focus of the study. Here, experts from the development and production departments of the participating companies came together to examine the parts following pre-evaluation carried out by the fka, as well as to develop and formulate lightweight design ideas. Impressions from the workshops are shown in Figure 10.

In all the workshops, the participants needed to work on lightweight design proposals by sketching and / or describing their idea as well as by carrying out their own assessment in the three categories of lightweight design potential, cost potential and implementation effort. This was necessary to achieve a multidimensional evaluation. All the aforementioned information was noted on lightweight design ideas sheets, which served as a basis for entries into the database. The set up and maintenance of the online database is an important accompanying working step alongside recording and presenting results as well as visualizing them for later use at other events of The Lightweight Forging Initiative.

In a final working point, the lightweight design potential of forged components in a car was identified by elaborating the ideas into lightweight design proposals using initial CAD designs or by approximate load calculations.

Examples of concrete lightweight design proposals obtained during this phase of the study are outlined in the Chapter 2.2.

2.1.2 Assessment of the Study on Lightweight Design Potential

The systematic disassembly of the reference vehicle uncovered approximately 3,500 parts for analysis. The analysis led to the formation of 399 lightweight design ideas, which were formulated in the three workshops by a total of 65 different people from 30 companies and research institutes. In total, 123 people took part in the workshops [1].

Context Analysis

A systematic overview of previous lightweight design potential in the powertrain and chassis is available.

Benchmarking

A reference vehicle was systematically disassembled, documented and recorded.

Three Hands-on Workshops

Facilitated workshops were held on the drive, chassis and other components.

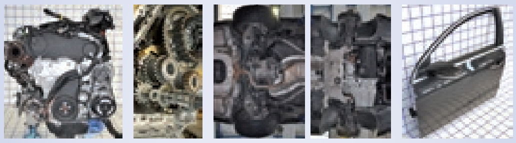
Gathering ideas and deriving lightweight design potential from these

Previously unknown lightweight design potential has been identified on forged components in a car and translated into concrete lightweight design proposals.

1. Determining the total vehicle weight

Reference vehicle:
125 kw / 170 PS
2.0 l Turbo-DI diesel engine
Double-clutch transmission, all-wheel drive
Total mass: 1,740 kg

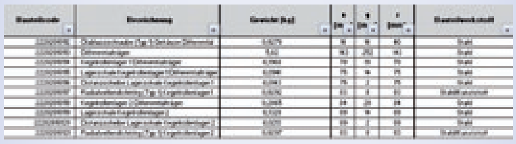
2. Disassembling the entire vehicle



Combustion engine | Transmission | Chassis | Door, seat, seatbelt, tow coupling

3. Listing and naming all individual parts

4. Analysis of individual parts



5. Weight of assemblies

6. Photo Documentation

- ISO views
- Detailed views
- Installation positions, where necessary
- Digital removal of manufacturer logo

7. Database implementation with proposals for lightweight design potential

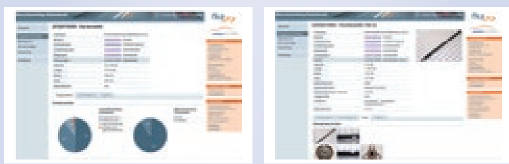


Figure 9: Project procedure for the study on lightweight design potential


Figure 10: Project participants and presentation of the components from the disassembled reference car during one of the three hands-on workshops

It makes sense to limit the description of the weight assessment of the reference vehicle to the overall evaluation as well as to the share of forged components. The vehicle under analysis has a total weight of 1,740 kg. As shown in Figure 11, the weight assessment subdivides the total weight into components from the car body (39 %), powertrain (23 %), chassis (16 %), interior (16 %) and electronics (6 %).

As it is primarily powertrain and chassis components which are of interest for lightweight design ideas using forging, all of the parts assigned to these categories underwent assessment in each case. In addition, 19 % of the interior (front seats and belt system) as well as 15 % of the car body (front doors and front bumper system as well as fastening elements) were included in the analysis.

This represents exactly 838 kg in mass or approximately 48 % of the whole car.

In a detailed weight assessment of the powertrain, it is no surprise to find that the combustion engine dominates with a 59 % share. The torque converter (double-clutch transmission) contributes to 16 % of the weight, just like the differential and transfer gearbox. The remaining 9 % comes from the four drive shafts (Figure 12, above).

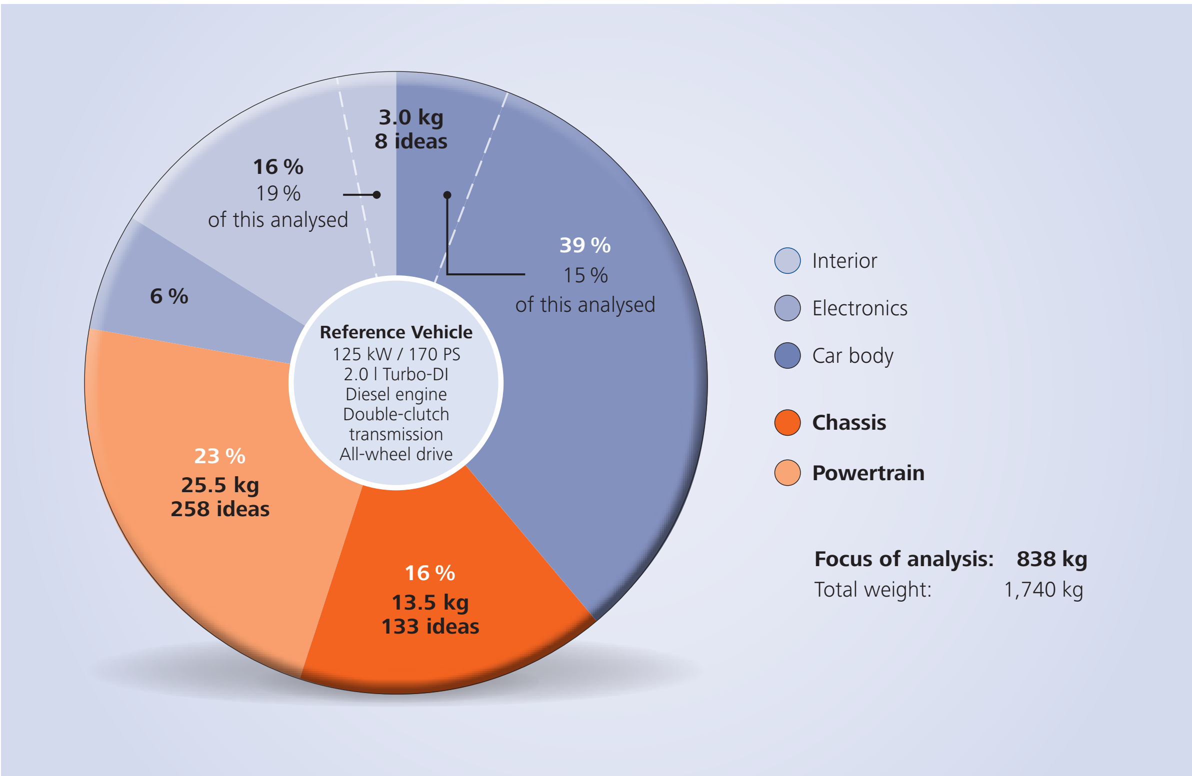


Figure 11: Weight of the reference vehicle

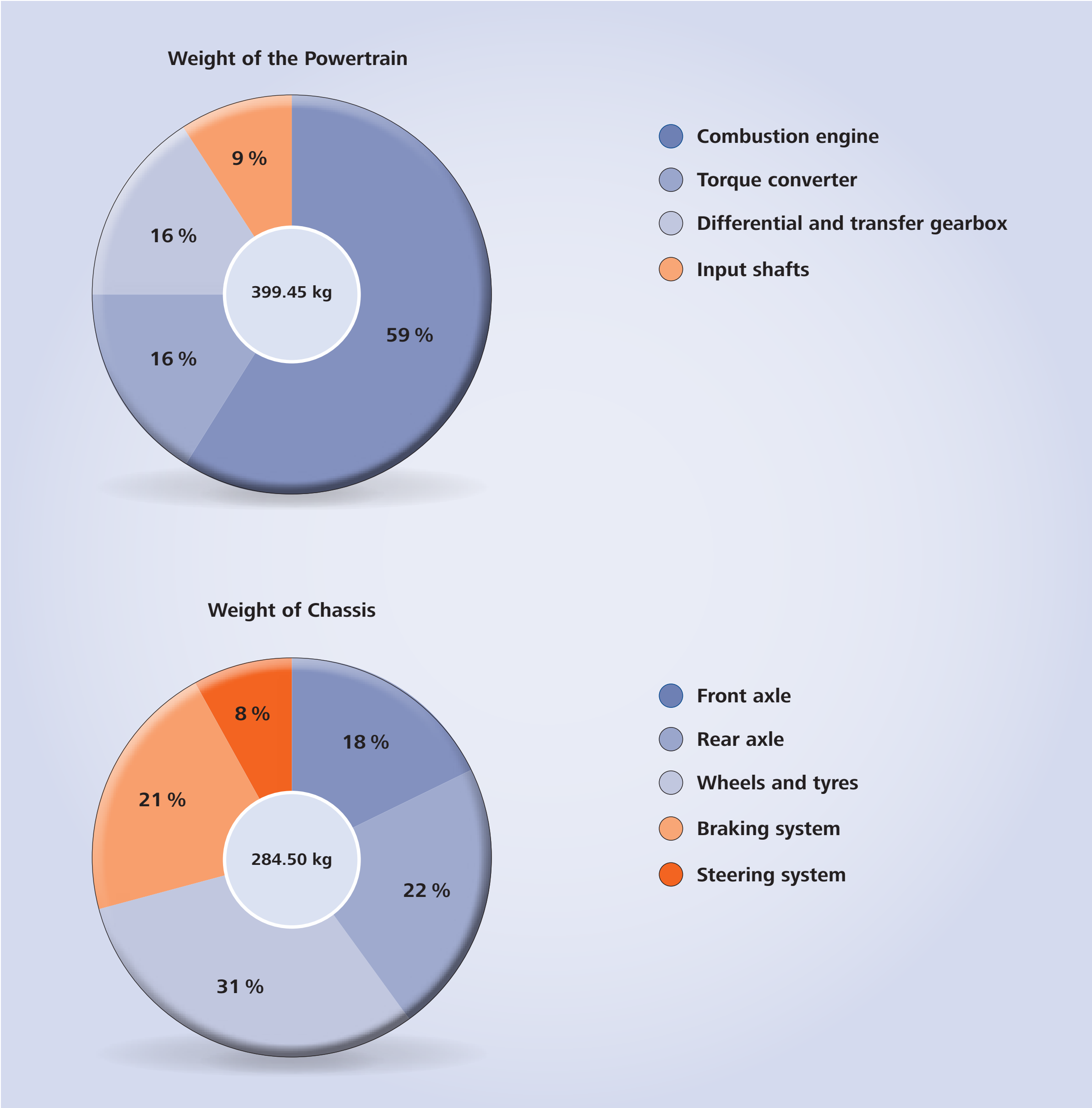


Figure 12: Weight of the powertrain and chassis

By contrast, the assessment of chassis weight reveals a more even distribution. Wheels and tyres make up 31 %, the front axle 18 % and the rear axle 22 %. The brake system contributes to 21 %, while the steering system is responsible for the remaining 8 % (Figure 12, below).

The results of the pre-evaluation carried out in advance of the workshops are shown in Figure 13. Here, it is clear that some weighty vehicle components cannot even be considered for a lightweight design potential analysis, as it is not possible for technical or economic reasons to produce them by means of forging. These components include the engine block, exhaust system and rear subframe. The remaining components from the powertrain and chassis are classified as

- wire and bar products,
- potential for forging,
- forged and
- fastening elements ("nuts and bolts").

Figure 14 provides a basic overview of the distribution of lightweight design ideas submitted and the lightweight design potential determined for the areas of powertrain, chassis and other components. Overall, a weight savings potential of 42 kg was identified, which corresponds to an astounding share of over 5 % of the total mass of 838 kg under analysis.

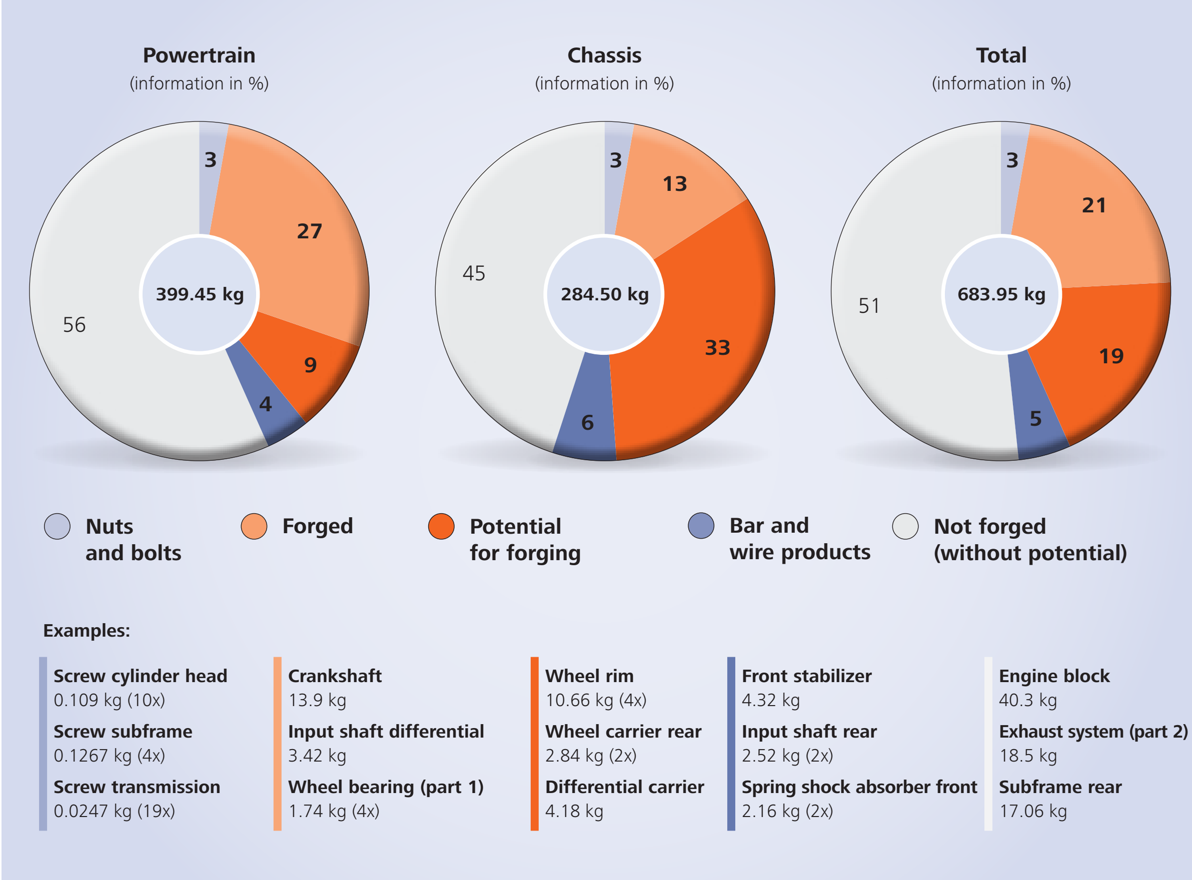


Figure 13: Percentage of forged components

In order to prioritize these ideas, two portfolios were set up for classifying the assessment of lightweight design proposals from the workshops on the powertrain and chassis, and for providing a very good visual aid. Here, the cost potential is plotted against the lightweight design potential. In addition, the estimated implementation effort is distinguished using different colours. Figure 15 and Figure 16 show two portfolio graphs. It should be noted that the values of the lightweight design potential are appropriately represented on the Y-axis in relation

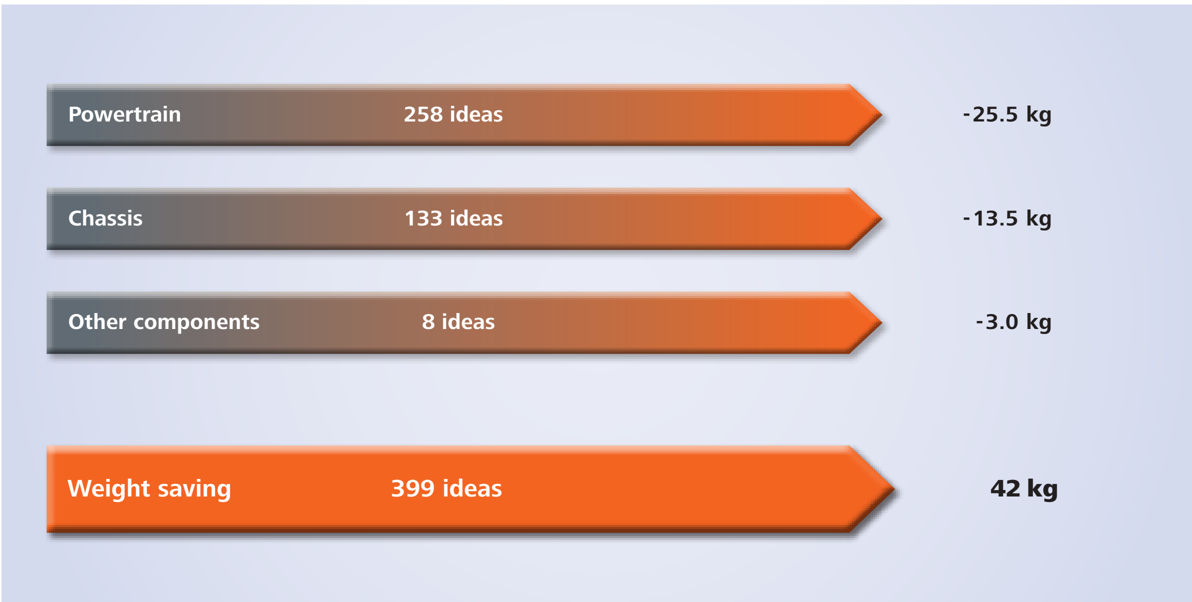


Figure 14: Evaluation and savings potential of the 399 ideas

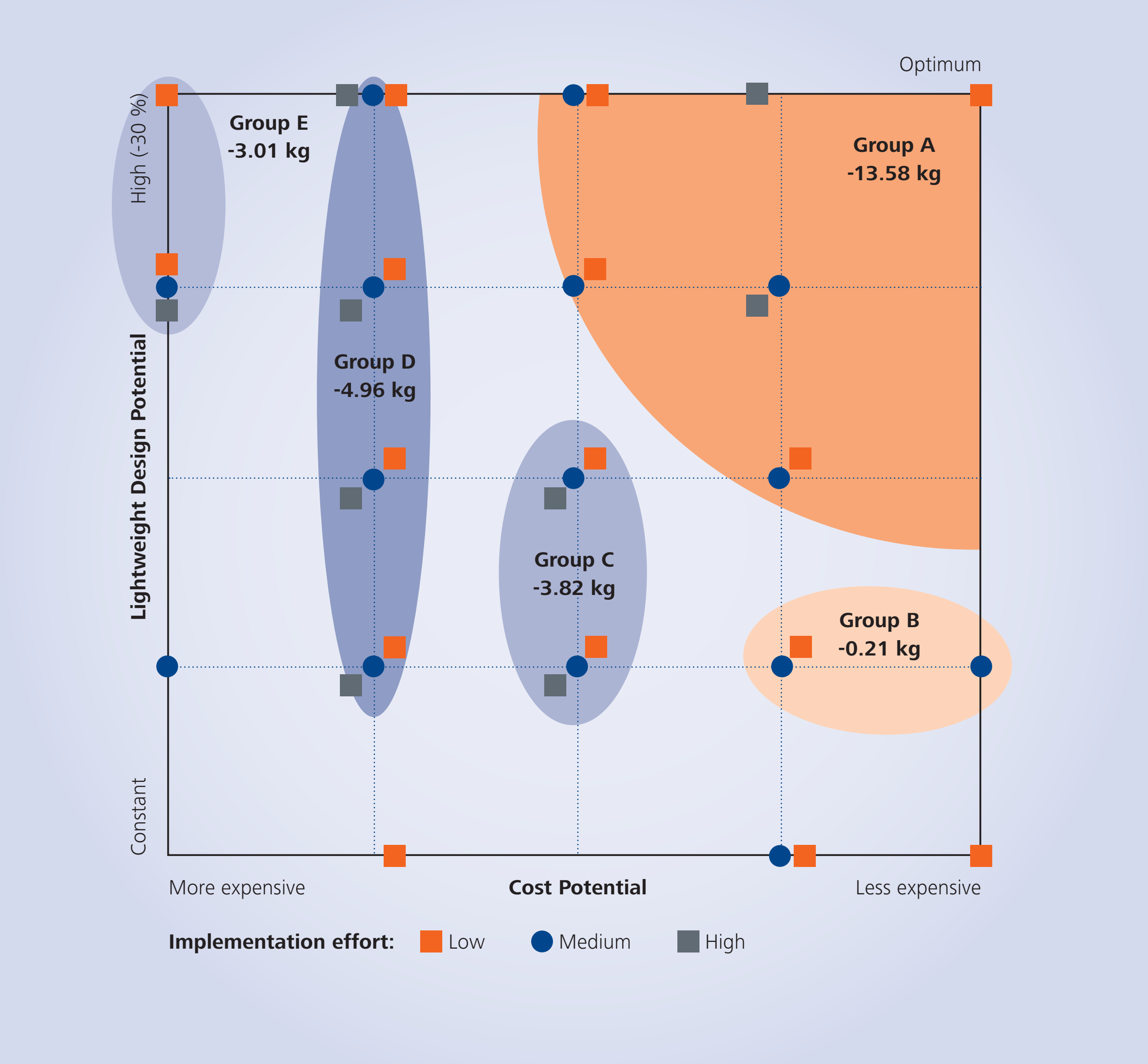


Figure 15: Portfolio for prioritizing lightweight design ideas in the powertrain

to the original value of "component weight" and that in most cases, one symbol represents between 5 and 36 lightweight design proposals.

Additional portfolio graphs in this form for the other components are not included here, as the focus of the analyses is on the areas of powertrain and chassis.

The prioritization shows that it is possible to make a classification according to groups: Group A represents the optimum between potential and costs. According to the estimation of the experts, both weight reduction and cost decreases are possible here. These ideas are thus "quick wins". Measures from Group E, by contrast, are apportioned to the area of full utilization of lightweight design potential, as the implementation effort on the development side is deemed to be generally more cost-intensive.

The cumulative graph in Figure 17 shows the overall result: The quick wins mentioned above represent cost-efficient lightweight design. A high implementation potential in the high series volume segment already results in a saving of approximately 25 kg. With the savings potential of up to 42 kg, full utilization of the lightweight design potential is depicted. By means of forging, it is thus possible through significant savings to reduce the analysed share of 838 kg of the vehicle weight to a remaining 796 kg.

Another representation of the lightweight design ideas is categorized according to:

- material lightweight design / alternative material use,
- lightweight potential through structural design and manufacture as well as
- conceptual lightweight design

This categorization is shown in Figure 18.

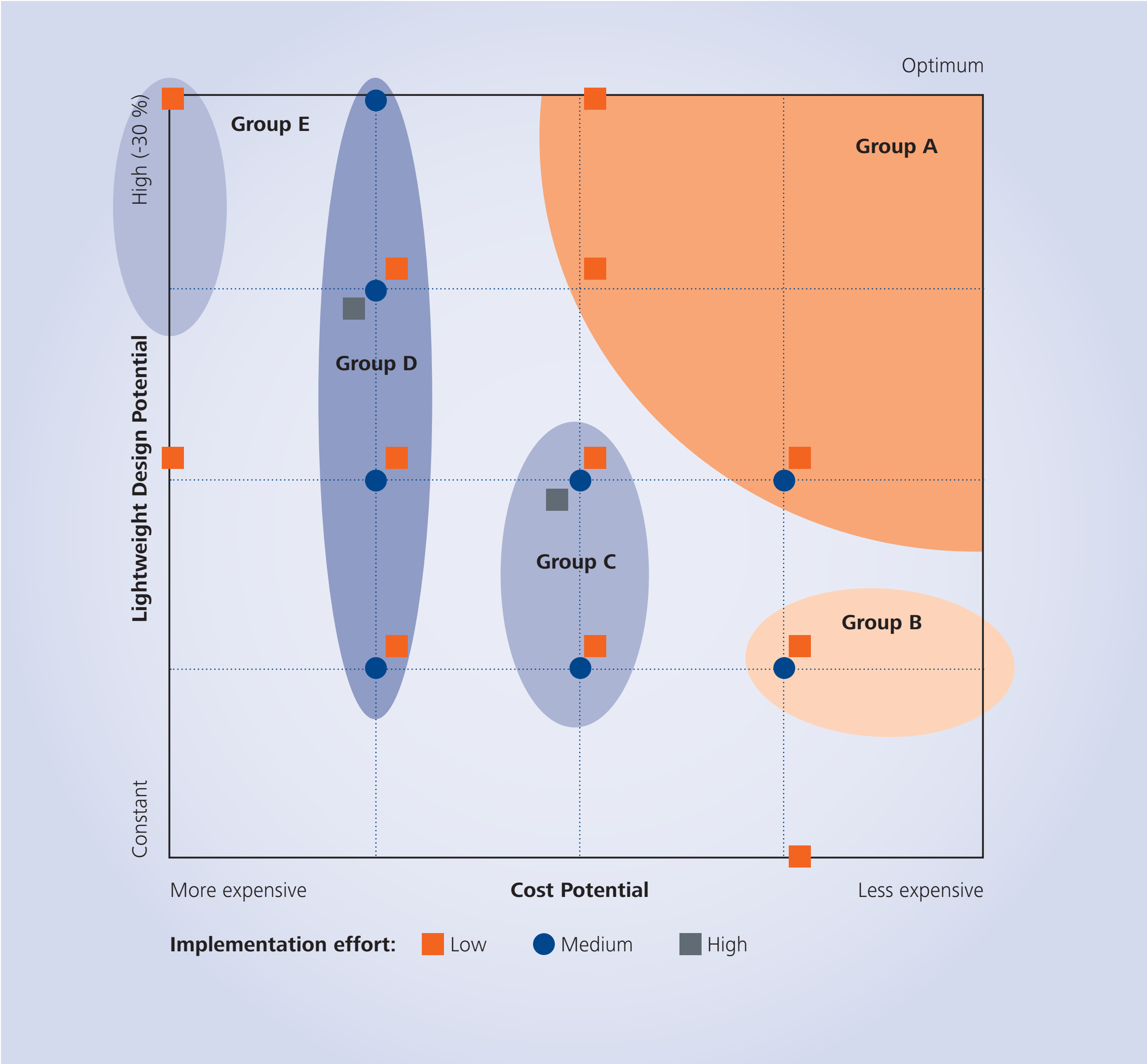


Figure 16: Portfolio for prioritizing lightweight design ideas in the chassis

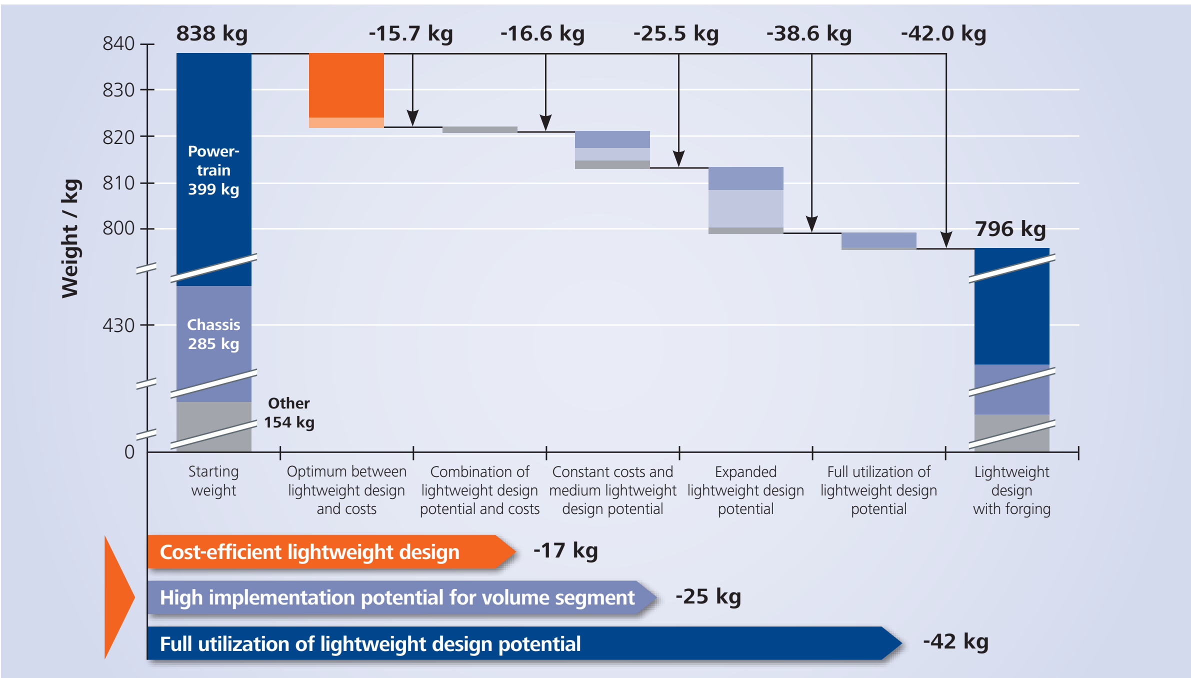


Figure 17: Cumulative representation of the lightweight design potential following prioritization

As can be seen, approximately 33 % of the lightweight design ideas are attributed to material lightweight design (Chapter 2.2.1) which, depending on the part, may demand a new structural design and topology optimization. With respect to this, a recommendation is made in the study to conduct additional analysis of lightweight design potential as part of an AiF (alliance of research associations) research project (Chapter 3).

Approximately 75 % of the lightweight design ideas hold potential resulting from the core expertise of the project participants, namely adapted designs on the basis of the continuous development of forging suitable for large-series production. Examples of these are outlined in more detail in Chapter 2.2.2. This confirms the soundness of the recommendation to intensify communication between the supplier and customer and, from the viewpoint of the vehicle manufacturer, to involve developers from the forging companies at an early stage to ensure that these ideas become established in serial production.

An additional 6 % or so of the ideas involve innovative concepts with more of a disruptive character (Chapter 2.2.3). These demand maximum effort in improving an existing system. Completely redesigning systems was not a focus of the project. Nevertheless, it is possible to recommend additional checks for technical feasibility, which in turn can only be achieved by intensive communication at a highly professional level between forging companies and customer design departments.

2.2 Examples of Identified Lightweight Design Potential

Naturally, it is only possible to present a limited number of the lightweight design ideas in this publication. For this reason, selected solutions are outlined which were generated from the systematic analysis within the workshops for the areas of drive and chassis. Here, it makes sense to differentiate between material lightweight design as well as lightweight potential through structural design and manufacture. Furthermore, conceptual lightweight design ideas are also presented which provide innovative ways of substituting current solutions.

The ideas described represent solutions that have not yet been developed to series maturity. On the one hand, there are initial draft-like proposals which require addi-

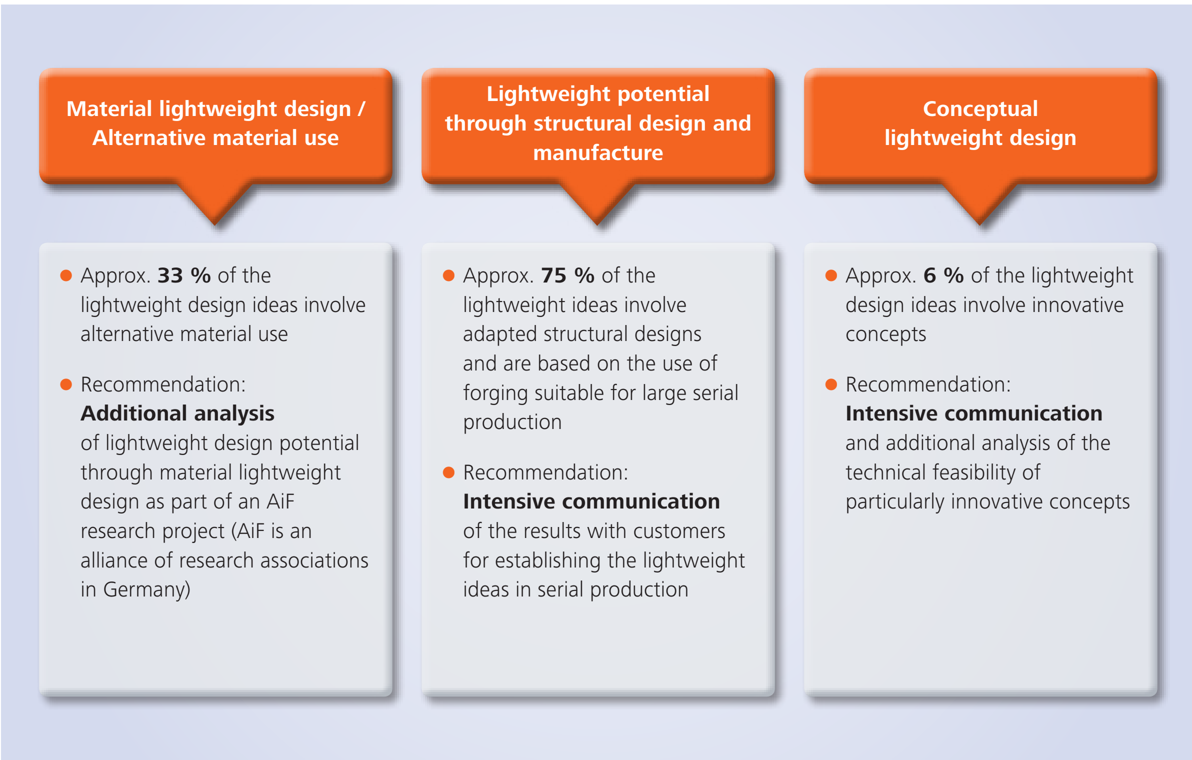


Figure 18: Assessment of the lightweight design ideas according to technologies

tional analysis using modern simulation from the area of simultaneous engineering. On the other hand, there are design proposals which have already been carried out for comparable tasks by developers at the forging companies. Furthermore, it cannot be ruled out that some proposals will be faced with system requirements which are not known among the participating steel manufacturers and forging companies. Thus the 3,500 parts also represent similar components of comparable vehicle types, thereby prompting new ideas. Conventional production technologies need to be questioned and alternative material and design possibilities revealed. As shown in the following, this process has already proven successful.

2.2.1 Material Lightweight Design Potential

What first springs to mind when thinking about how to achieve "lightweight design" is understandably the substitution of an existing material that has a higher specific weight with one that has a lower specific weight. Thus, to the general public, "lightweight" is associated with the metals aluminium, magnesium and titanium or with carbon-reinforced plastics (CRP). Several examples, primarily from chassis technology, show an increasing percentage of components which are forged from aluminium alloys [11], [16]. Nevertheless, steels as a forging material can certainly stand up to this competition. The arguments in favour of steel include optimum mechanical properties and manageable costs. Furthermore, several new developments are measuring up well on the weighing scales, such as cost-efficient higher strength steel grades for forged parts, which the steel manufacturers in The Lightweight Forging

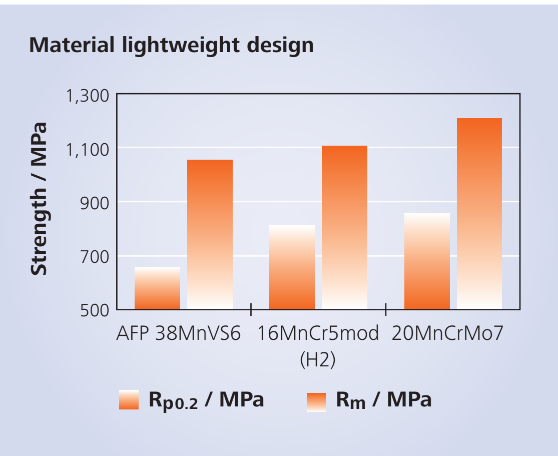


Figure 19: Comparison of load-bearing capacity of dis-persion-hardening and HDB steels

Initiative are introducing in the project and thus in the workshops.

Particularly the requirements placed on the parts from the areas of powertrain and chassis, which are the subject of analysis in the project, demand higher mechanical values. This means that often heat-treatable steels are drawn upon instead of the more inexpensive dispersion-hardening steels. Both the higher alloy costs as well as the costs for additional heat treatment and crack detection result in considerable drawbacks in terms of price and process engineering. This gap is currently being filled by the development of high-strength ductile bainitic (HDB) steels [17]. These can be processed without additional heat treatment, yet achieve mechanical values comparable to those of quenched and tempered steels. With respect to processing costs, HDB steels are thus similar to the cost-efficient dispersion-hardening steels.

A steel grade already available on the market is 20MnCrMo7 [18]. Through controlled cooling from the forging heat, a bainitic grain structure is generated in this steel. A second example is the steel grade 16MnCr5mod (H2). This was developed in a cooperative project between two manufacturers from the steel and forging industries [19], [20]. Figure 19 shows the characteristic values of both these steels compared to the dispersion-hardening steel 38MnVS6.

What both steels have in common is that their properties are generated directly out of the forging heat. To achieve this, however, a very precise process is demanded during forging itself as well as highly targeted and controlled cooling rates following hot forging [21].

The use of these improved material properties plays a role in several examples of the lightweight design analysis. The fundamental optimization approach is always to achieve a decrease (often local) in material thickness or to reduce material use through the higher strength obtained by switching to a higher-strength steel.

In engines, this can be used, for example, for the injector clamping bracket shown in Figure 20. As a forging with optimized design due to the use of a higher strength steel compared to sinter material, a weight-saving potential of approximately 20 % is demonstrated (Figure 21).

Figure 20: Clamping bracket for injectors

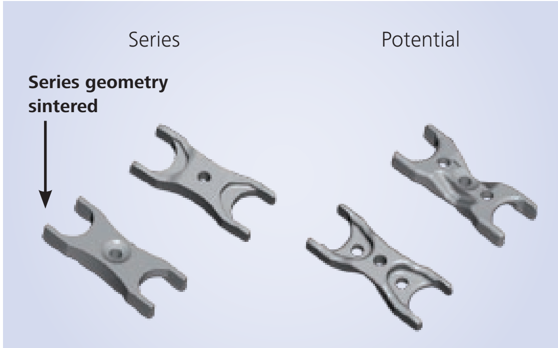


Figure 21: Clamping bracket for injectors – savings potential when using a higher strength material and subsequent design modifications

Figure 22: left – input shaft front, right – coupling rod front

Two parts from the powertrain and chassis may also be produced using this lightweight design idea. From the powertrain, the front drive shafts produced in this way likewise reveal a potential weight saving of 20 % (Figure 22, left). From the chassis, the coupling rods demonstrate an estimated weight-saving potential of 5 % (Figure 22, right). In the case of these coupling rods, one proposal is to substitute the dispersion-hardening steel used to date with HDB steel.

Another example of lighter dimensioning as a result of switching to a higher strength and tougher steel is the tow coupling, which is a representative of add-on components. For the tow coupling shown in Figure 23, a possible weight reduction of 10 % is determined.

One area of weight-saving potential which has not yet been presented here is achieved through the use of fastening elements of a higher strength class and correspondingly smaller dimensioning. From the study, an idea emerged which involves reducing the dimensioning of screws for fastening the connecting rod cap and shaft from M8 to M7 as well as finding other ways of decreasing the weight of the forged connecting rod (Chapter 2.2.2). This also leads to secondary lightweight design potential with respect to the crankshaft and the mass balancing system.

Particularly by taking into account the large number of fastening elements in a vehicle, the low savings which

Figure 23: Ball head of the tow coupling

Figure 24: Crankshaft of the reference vehicle

the individual elements bring can soon add up to a remarkable savings potential. This leads to the idea that the principal design criterion may not be the components that need to be fastened but rather the strength of the fastening elements themselves.

2.2.2 Lightweight Potential through Structural Design and Manufacture

Through consistent application and pursuit of proven FE methods at an early phase of development, additional lightweight design potential may be tapped through structural design and production considerations, as the following examples from the analysis of lightweight design potential show.

The forged crankshaft, as a complex engine component, is shown in Figure 24.

Through optimizations to the geometry of the crankshaft, which has a mass of 13.9 kg, the material in the marked area of the pin bearings may be reduced by forging recesses into it (Figure 25, left and centre). A rough calculation of imbalance reveals additional material savings on the counterweights, too (Figure 25, right).

The lightweight design potential that may be achieved using higher strength fastening elements for the connecting rod caps, as outlined in the previous chapter, can also be used for changing the geometry of the connecting rod. Retaining the required wall thicknesses, the connecting rod (Figure 26) can now be designed narrower and thinner. Furthermore, such weight reductions in moving masses result in greater secondary effects in the engine, which in turn prompt additional improvement potential in bearings or balancer shafts.

By taking these secondary effects into account, the weight-saving potential in the engine amounts to approximately 1 kg.

Additional lightweight design potential may be tapped by fully exploiting the shaping possibilities offered by forging. Figure 27 shows the common rail that was analysed from the reference vehicle; Figure 28 compares the common rail from Figure 27 with a proposal for reducing component cross-sections.

In this case, it is essential to take into account the insights described in [22] relating to the use of materials which permit considerable upsetting of the steel without causing a drop in their load-bearing capacity. In addition, the use of a low-sulphur dispersion-hardening steel needs to support the material savings. As shown

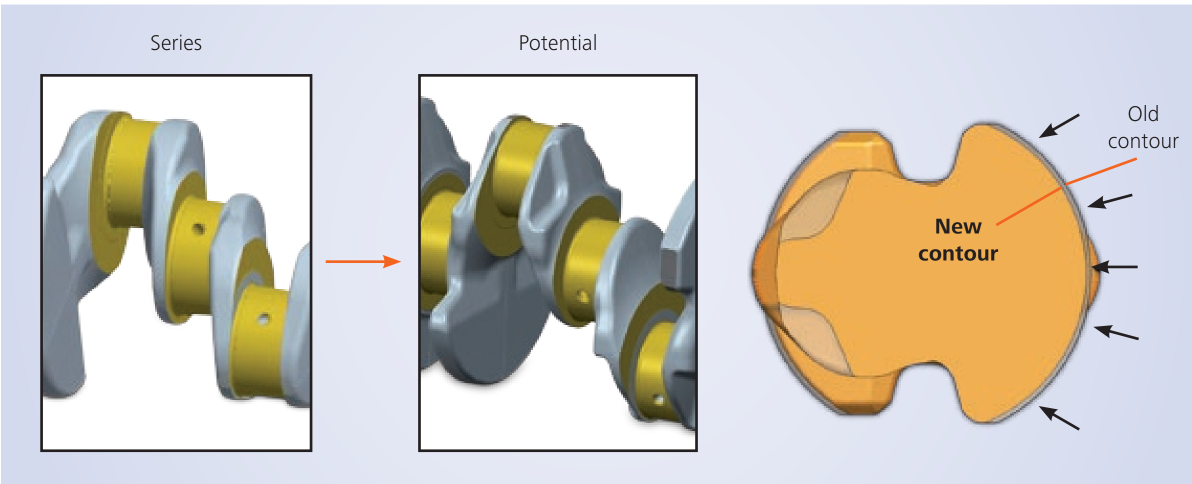


Figure 25: Crankshaft – Comparison of the series part and the lightweight design proposal

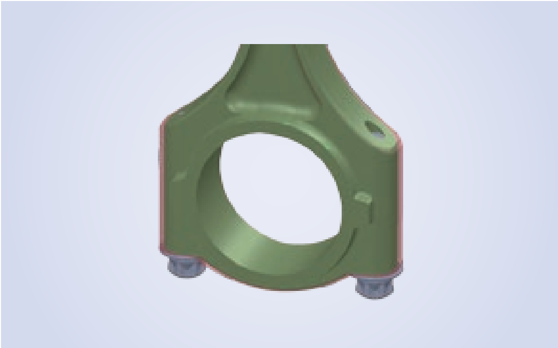


Figure 26: Connecting rod – Geometrical savings potential through use of higher strength screws and reduction of screw diameter

in the comparison between the series part and the lightweight design proposal, the equivalent stress is almost identical.

The optimization potential just described relates to elements of the engine in the reference vehicle; in the following, the ideas concern components in the transmission or transfer gearbox.

In the first example, one key insight is that in the case of crowned teeth which bear the load in the centre, the main bending load of the teeth lies in the centre of the tooth. It should thus be possible to minimize material at the tooth ends. The gear wheel component for the 5th gear on the input shaft shown here has a mass of 0.41 kg in its series form (Figure 29). Subject to additional strength calculations which still need to be carried out, this mass may be reduced by 20 %. In Figure 30, the weight-optimized design is shown in a tilted top view and in cross section.

As a second example, Figure 31 shows the shaft in the transfer gearbox with a weight of 1.38 kg. The lightweight design potential is identified below the hypoid gears, i.e. in the transition area to the shaft, and amounts to around 20 % (Figure 32). Correspondingly, it is thus possible to forge an annular recess which no longer needs to be machined, depending on imbalance requirements. Furthermore, a hole can be introduced into the shaft centre. This hole cannot be produced cost-effectively using forging. While this generates a small additional effort in soft machining, the process should nevertheless prove cost-efficient when calculating "Costs per kg forged part" [23].

Figure 27: Common rail

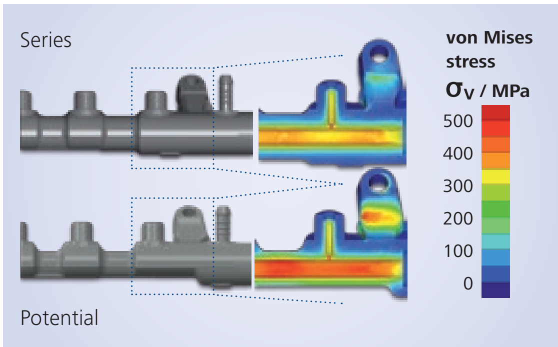


Figure 28: Common rail: Comparison of geometries

Figure 29: Gearwheel 5th gear of input shaft

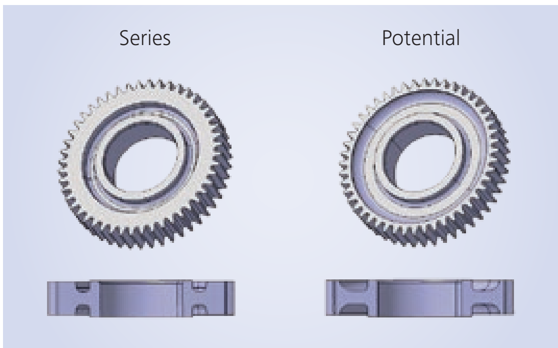


Figure 30: Gearwheel 5th gear: Comparison of the original and modified profile

Figure 31: Shaft of the transfer gearbox – real part

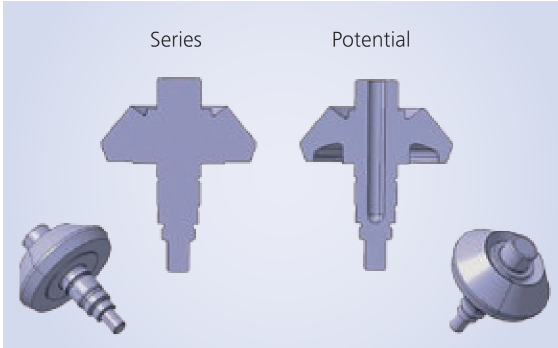


Figure 32: Shaft of the transfer gearbox – Comparison of the series part and the lightweight design proposal

Further along the powertrain, behind the transfer gearbox, are the companion flanges for connecting the input shafts. The starting mass here amounts to 1.2 kg for the left and 1.9 kg for the right flange (Figure 33). The following example is a lightweight design proposal for the companion flanges of the rear drive. The weight-saving potential draws upon several proposals. The most notable is the deviation from a rotationally symmetric geometry, as the contour between the bolt holes may be provided with considerable recesses. Furthermore, the cylindrical form of the shaft is interrupted by radial pockets forged into the part. Intensive material savings are achieved not least through the conical inner geometry which is designed much deeper than the series part. However, these initial analyses also reveal that torsional stiffness decreases by approximately 14 % with this solution. The measures presented add up to a weight-saving potential of around 0.21 kg, which makes a saving of 21 % in the case of the left flange (Figure 34).

For the input shaft shown in Figure 35, with a mass of 1.34 kg, a weight-saving potential of around 5 % was demonstrated. This was achieved through a weight-optimized design for forging in the form of material removal at the transition area from the hollow shaft to the flange, as shown in Figure 36.

In the chassis, a large number of lightweight design ideas were found for the four wheel bearings assembled in the reference vehicle (Figure 37). While this highlights the great significance of these components, it also points to the fact that, as rotationally symmetric parts, their design to date has been dominated by economic considerations rather than with respect to lightweight design aspects.

They contribute a total of 6.96 kg to the vehicle weight, and thus call for lightweight design potential to be tapped here.

Figure 33: Companion flange input shaft – rear right

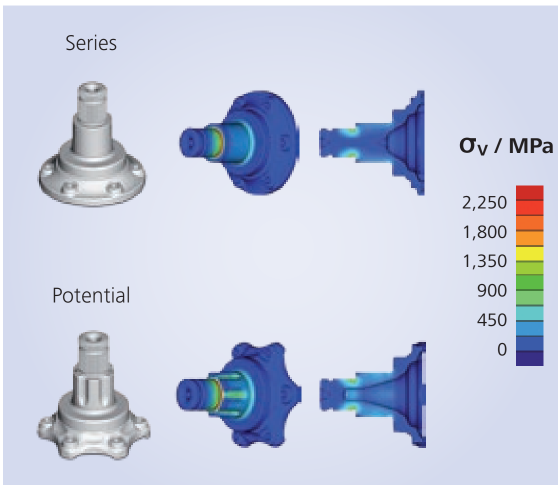


Figure 34: Companion flange of the input shaft (rear) – Comparison of the series part and the lightweight design proposal

Figure 35: Input shaft – real part

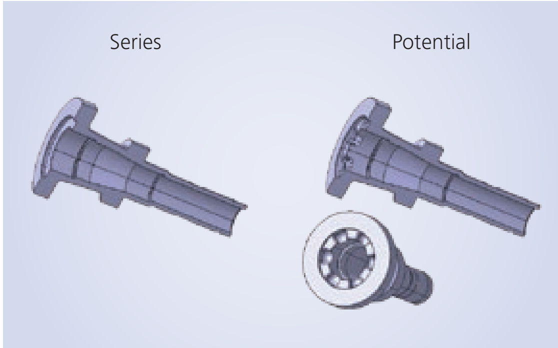


Figure 36: Input shaft – Comparison of the series part and the lightweight design proposal, and real part

The solution presented in the following is highly ambitious and presents process engineers with a challenge. Initially, the rotationally symmetric flange is given a pentagonal external geometry by means of recesses. Furthermore, five individual contact surfaces of the required thickness are provided for mounting the wheel. Between these contact surfaces, the material is produced considerably thinner than is the case with the series part. In addition, the wheel hub journal has recesses, and on the side facing away from bearing journal, a stiffness optimized internal contour is proposed. Besides this, the centring ring used to date for centring the wheel rim hole contains several recesses, rendering the part highly challenging to produce by means of forging (Figure 38). The total weight-saving potential for four parts has been calculated as 2.88 kg.

Similar considerations have led to the following lightweight design proposal for the companion flanges of the propeller shaft (Figure 39), each of which weighs 0.56 kg in the reference vehicle. By reducing material in the area of the bolt holes and on the opposite side to the wheel hub, as shown in Figure 40, the weight-saving potential lies at approx. 20 %.

It seems evident from the previous examples that in lightweight design analyses, the supposedly complex components of the powertrain and chassis hold the greater share of weight-saving potential.

By taking another look at the numerous and indispensable fastening elements, another radical idea emerges. The geometry of a hexagon nut with flange undergoes fundamental change through material savings on the hexagon surfaces using the design possibilities offered by cold forging (Figure 41).

This measure requires verifications of strength in simulation and testing. Figure 42 shows example

Figure 37: Wheel bearing left

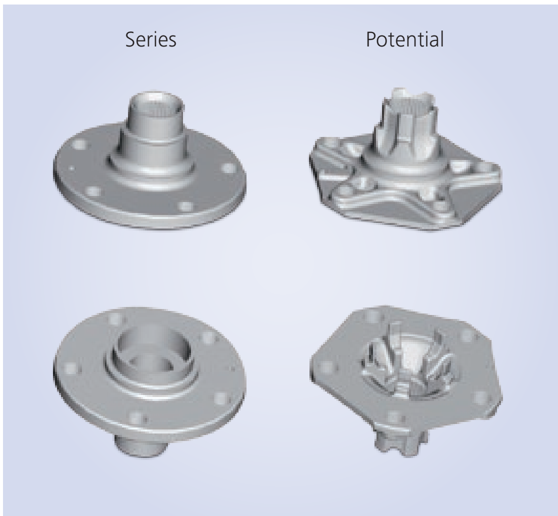


Figure 38: Wheel bearing – Comparison of the series part and the lightweight design proposal

Figure 39: Companion flange of the drive shaft

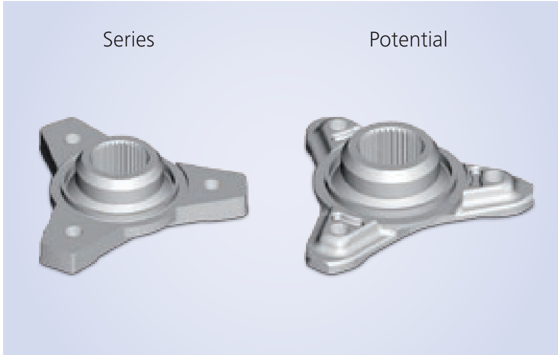


Figure 40: Companion flange of the drive shaft – Comparison of the series part and the lightweight design proposal

results of an FEA analysis of a hexagon nut and a lightweight design nut with flange using loads according to DIN EN ISO 898-2 [24].

By comparing the results of the structural-mechanical simulations for the reference geometry with the results for the lightweight design geometry, similar values are obtained for equivalent stress (von Mises) and plastic strain. In principle, it is thus possible, within the given structural-mechanical boundary conditions, to achieve minimization of mass through reducing partial volumes that do not contribute directly to load-carrying capacity and mechanical function [25].

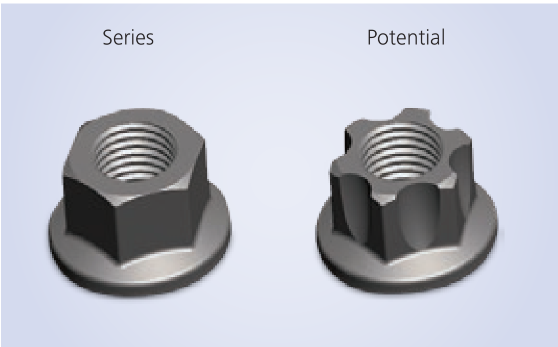


Figure 41: Hexagon nut with flange and following weight optimisation

This patented lightweight design nut is stated as achieving a mass reduction of up to 20 % compared to conventional standard nuts using conventional fastening technology and omitting heat treatment (tempering and quenching) for achieving the strength class "10" according to DIN EN ISO 898-2 [26].

Although in absolute terms, only a few grams are saved per part, the high number of such fastening elements renders this weight-saving potential highly interesting.

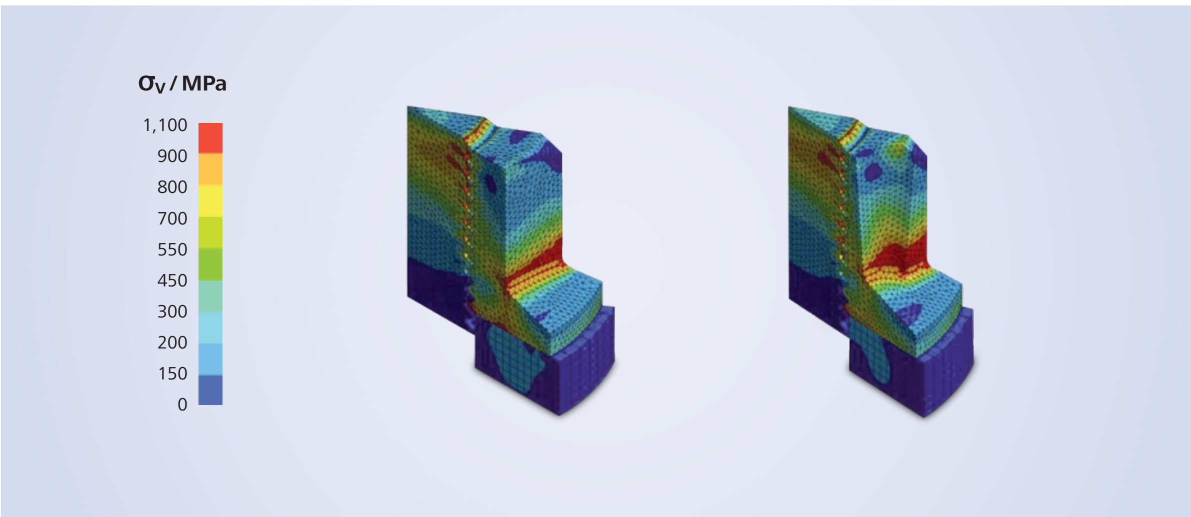


Figure 42: Equivalent stress state σ_V (von Mises) using loads according to DIN EN ISO 898-2 left: Hexagon nut, right: Lightweight design nut, each with flange, M 14 x 1.5

2.2.3 Conceptual Lightweight Design Potential

Lightweight design generated by means of new concepts generates greater implementation hurdles, as it is of a disruptive nature and thus initially subordinate to established products. However, by exploiting the advantage of lower weight, they are certainly in a position to be well received in future.

One example of such a lightweight design proposal is shown in Figure 43. Here, the implementation possibility still needs to be tested out. The proposal foresees that instead of a flange connection using screws, torque transfer is achieved via a Hirth face gear, which is highly capable of bearing loads and which may be produced ready-for-assembly both on the output shaft as well as on the tripods. This would involve substituting the six individual screws used to date with a single unit nut. The proposal thus not only leads to a reduction in weight of 828 g or 25 % but also to the omission of the welding process and to a reduction of effort in vehicle assembly.

2.3 Summary and Conclusion

In the largest pre-competitive joint project known as "The Lightweight Forging Initiative", 15 forging companies and 9 steel manufacturers have carried out a study on lightweight design potential. The goal was to demonstrate and provide a detailed description of the lightweight design potential of forged components as well as to implement concrete lightweight design proposals for a passenger car.

Contents of this study included

- a context analysis for obtaining an overview of previous studies and publications on the topic of lightweight design,
- benchmarking the components of a reference vehicle, which was systematically disassembled, recorded and documented for this purpose,
- identifying and documenting lightweight design ideas using three different hands-on workshops and
- deriving lightweight design potential as well as implementing substantiated lightweight design proposals.

This project has generated 399 formulated proposals with an overall weight-saving potential of more than 42 kg. These weight savings are derived from the following analysed assemblies:

- powertrain,
- chassis and
- other components

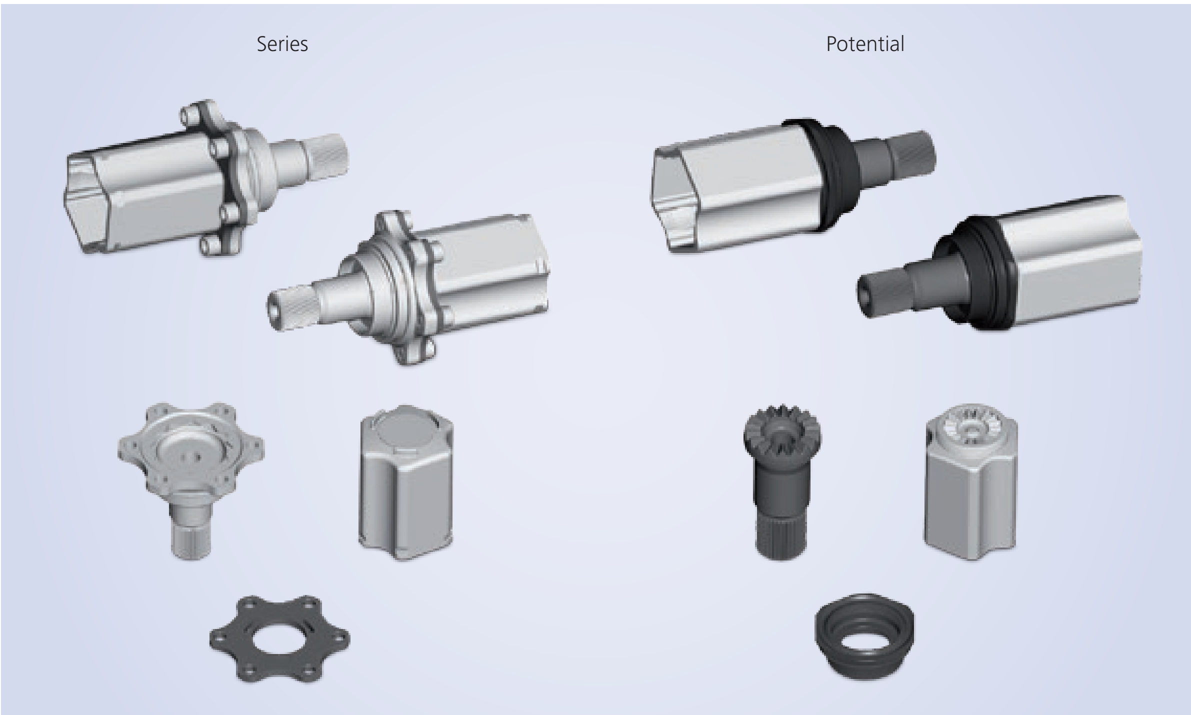


Figure 43: Conceptual lightweight design in the powertrain

The proposals were categorized as ideas relating to:

- material lightweight design,
- lightweight potential through structural design and manufacture as well as
- conceptual lightweight design.

In addition, the cost impact and implementation effort of each proposal were estimated, ultimately leading to classification of the overall implementation potential. The multi-dimensional approach leads to useful results and is of great value for additional bilateral projects between material and component suppliers together with automotive customers.

3 Transfer of Insights to Development Processes and Research Projects

3.1 Transfer of Insights to Development Processes

It goes without saying that a wealth of development know-how existed among the participating forging and steel manufacturing companies prior to the study on lightweight design potential and that, correspondingly, a majority of the insights gained from the project are not completely new. Quite the contrary: Published developments or even patented processes were also drawn upon in the study. Through the additional ideas and input which were the result of cross-sector and interdisciplinary cooperation, the participating experts achieved an overall weight-saving potential of 42 kg in the reference vehicle by exploiting specialist know-how with respect to materials and heat treatment.

The primary result of the joint project is the ability to work with these interdisciplinary ideas, and to transfer them to new challenges faced by the relevant supplier with each new customer inquiry that they receive. The project was particularly beneficial to those companies which have worked less intensively to date on optimizing the material of their products.

Through vehicle disassembly and the impressions of the highly haptic hands-on workshops, all participants have gained a much deeper insight into the state of the art. It also highlighted the applications in which automotive customers are already using forgings as well as potential applications which had not been identified previously.

Finally, the joint project continues the rethinking process that began a long time ago. Cooperation – including with research institutes and associations – is being received much more positively. Development times can be reduced by early cooperation, while inefficient and thus costly development loops should be avoided with steel manufacturers and forging companies.

3.2 Research Approaches

In outlining the insights gained from the study on lightweight design potential described in Chapter 2, the need for additional research was pointed to. The Lightweight Forging Initiative is proposing a lead technology project for SME to AiF (an alliance of research associations) / BMWi (Federal Ministry for Economic Affairs and Energy).

The goal is to fully exploit the lightweight design potential of forged components in automotive engineering by developing new processes in forging and development as well as by using more efficient steels and heat treatment operations.

Here, the leading research institutes from the process chain of steel manufacture – forging – heat treatment – machining have been integrated and have worked on research clusters based on the results of the study on lightweight design potential. These research clusters will be developed over the coming three years together with 50 companies from the industry.

The activities named here thus emphasize the importance of the cooperation between steel manufacturers and developers from forging companies as a solid basis for a professional development partnership in the automotive industry. This task of this cooperation is not only to find answers to the challenge of emission reductions but also to implement production-ready solutions at an early stage.

Additional Lightweight Design Potential with Forging

Beyond the examples presented above, the performance of the industry is also demonstrated through optimization measures developed outside of the workshops on lightweight design potential. In the following, individual lightweight design solutions will be presented which were not developed specifically for the reference vehicle, but were already being used in other applications.

Gearwheels are attracting particular attention due to the high total number of them in transmissions. The arm and wavy profiles shown in Figure 44 form the starting point for an innovative lightweight design concept. Through new and patented design, the material below the tooth ends may be reduced by a third. At the same time, the gearwheel can be optimized with respect to distortion behaviour using heat treatment processes. Due to the optimized fibre flow of this gearwheel, the advantages of a forged vehicle component can be exploited to the full, as the part can be adapted to the load case, ultimately leading to the goal of a higher fatigue limit [28]. This results in light yet high-strength speed and differential gears.

Accordingly, Figure 45 shows a CAD study on the further development of transmission parts with the aim of reducing the rotatory masses and increasing the power density of the parts. Reduced wall thicknesses and the move away from a rotationally symmetric design are pursued consistently here.

The same is true of the precision-forged speed gear shown in Figure 46. Starting with a classic rotationally symmetric cross section, the part was provided with a sufficient number of stiffening radial arms between the

Figure 44: Wavy gearwheels

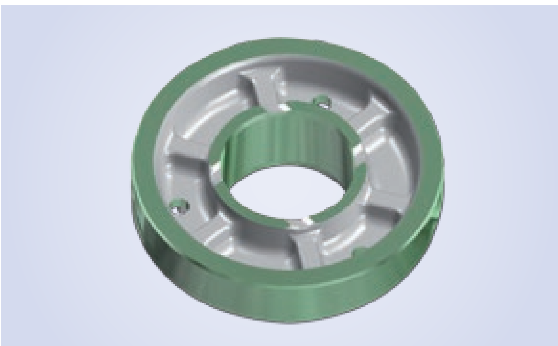


Figure 45: Gearwheel study for reducing rotatory masses

Figure 46: Near-net-shape design of a precision-forged speed gear

wheel hub and the gear rim. Furthermore, material was removed between these arms by means of punching to achieve maximum weight savings.

Finally, the continuous further development of differential pinions (Figure 47) should be mentioned as an example of potential lightweight design. Optimizing the tooth geometry leads to an increase in load-bearing capacity and thus, under constant load requirements, to a downsizing of the differential through a more compact design.

One proposal generated from the idea of substituting a cast part with a forged one combined with a greatly modified geometry is shown in Figure 48. For a crankshaft bearing of a ship engine, a weight-saving potential of 0.28 kg may be achieved using a load-optimized forged part.

Through a process combination of traditional cold forging and radial forging, the hollow shaft of an automatic transmission shown in Figure 49 is generated. This is also a part not found in the reference vehicle. Besides optimized material use and the resulting lightweight design, the cold forged lubrication grooves are also noteworthy, as they provide the hollow shaft with a functionally optimized internal contour [16].

Similar to the situation with fastening elements, the savings potential of smaller parts must always be seen as part of the overall weight-saving potential. In the case of the chassis bearings shown in Figure 50 and Figure 51, the weight difference multiplies with the number of bearings in a vehicle. Figure 50 shows a rear-axle bearing assembled four times in the vehicle. This bearing is not only hollow in design but is also provided with an internal undercut. The internal contour

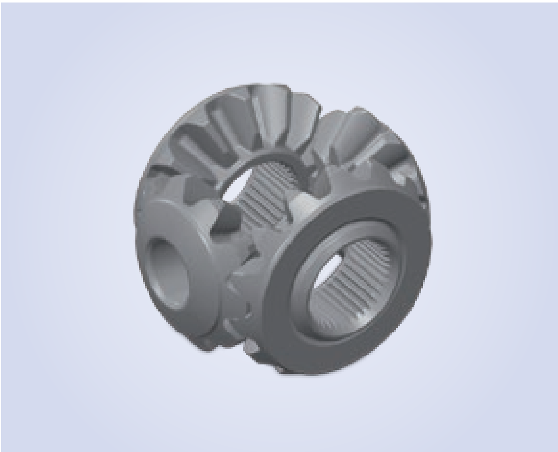


Figure 47: Optimized differential bevel gear set

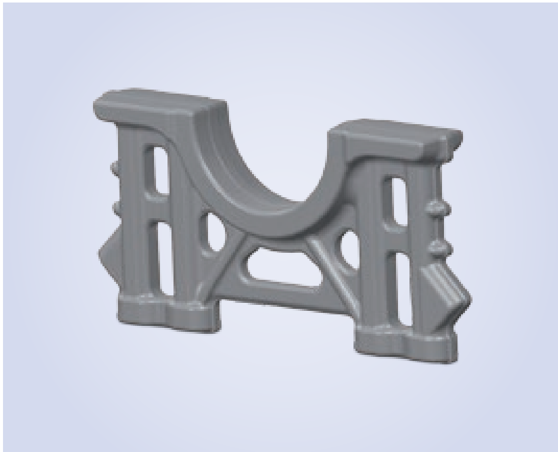


Figure 48: Crankshaft bearing as a forged part with design optimization

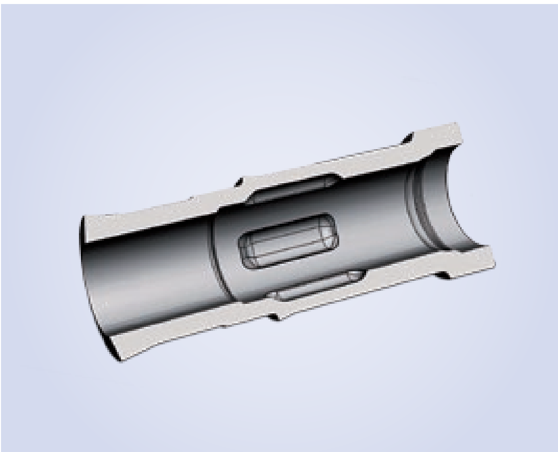


Figure 49: Hollow shaft of a modern automatic transmission with weight-optimized design

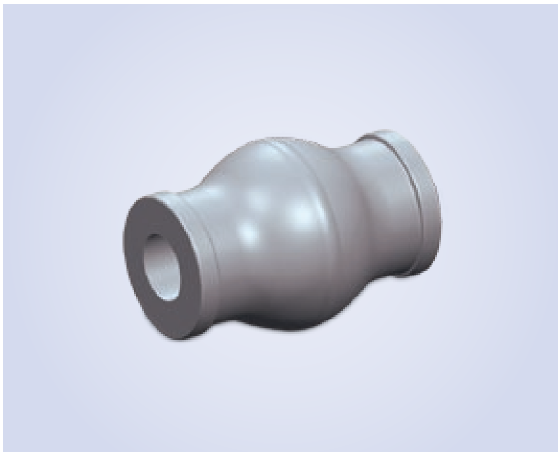


Figure 50: Chassis bearing for rear axle made of aluminium

may be generated cost-efficiently by means of cold forging. In addition, material lightweight design was used for this bearing, with steel being replaced by aluminium and with the generation of a larger contact surface.

An example of a material lightweight design approach already outlined is represented by the chassis bearing for a wishbone of the front axle (assembled twice in the vehicle). Here, a higher strength steel was used as a substitute material. At the same time, the undercut between the contact surfaces shown in Figure 51 was employed as a design optimization principle of cold forging.

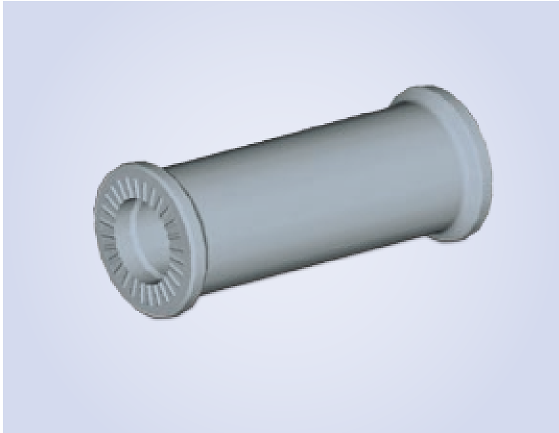


Figure 51: Chassis bearing for front axle wishbone made of steel

5 Summary and Outlook

As a result of informal talks at the SCT steel conference for automotive applications in 2011, a consortium of 9 steel manufacturers (Steel Institute VDEh) and 15 forging companies founded The Lightweight Forging Initiative. In a first multilateral project, a study on lightweight design potential was carried out from February to October 2013. In this study, the lightweight design potential of a reference vehicle (significant series volume, estate car, diesel, double-clutch transmission, all-wheel drive) was developed within the context of three workshops following disassembly of the car into its individual components. The result was a weight-saving potential of 42 kg or over 5 % based on the vehicle areas analysed and relevant to forging. The study was conducted and documented by fka Forschungsgesellschaft Kraftfahrwesen mbH Aachen, an automotive engineering research institute.

The outcome is seen as positive by both the steel manufacturers and the forging companies. The steel manufacturers welcome the improved communication between the forging companies and the steelworks [7]. Furthermore, the dialogue has confirmed that a high number of similar but not quite the same materials are used, which considerably increases inventories and production effort as well as costs thereof. What also emerged was that materials were not being used to their full potential, both as material themselves as well as with respect to properties. Similarly, the experts uncovered materials whose technical possibilities – taking into account relevant safety values – were not being exploited fully or even at all [21]. The participants agree that the readiness of the OEMs to use new steels in their vehicle components needs to evolve. What can still be seen is a greater willingness to accept the effort involved in adapting a part by switching to newer, supposedly lighter non-ferrous materials than the readiness to achieve weight savings by using high-strength steel with appropriate changes in geometry.

The joint cooperation of The Lightweight Forging Initiative has shown that these hurdles should be easier for automotive manufacturers to tackle than was previously thought. Furthermore, it should be possible to present the ideas and concepts to the manufacturers in a form which would not have been possible for individual members of the Initiative [28].

From the viewpoint of the forging companies, the topic is not new in itself (Chapter 1). Instead, the motivating factor for participating in the Initiative was the cross-sector bundling of know-how across the entire process chain. Through this, the industry practitioners recognize to an even greater extent the conflicting areas of weight reduction, cost potential and, above all, implementation effort. For the forging companies, it is therefore essential to include material and forging potential in the early phases of system and part development. Here, there are tried-and-tested simultaneous engineering processes. However, these need to be used for considerably more components than at present. The purchasing process of the automotive manufacturer should take place in earlier phases of development, namely when lightweight design proposals of the supplier can still flow from material or production engineering into part design.

It should also not be forgotten that in the case of the lightweight design ideas for the powertrain with a weight reduction volume of 25.5 kg, 7.9 kg may be achieved only with additional costs of 10 to 20 % This may be compensated for in part by means of other lightweight design components which can be produced more cost-efficiently than in the past. However, the fact remains that, overall, a lighter car design will lead to slightly higher procurement costs. What is positive is the willingness of car buyers to pay more for ecological solutions, as verified in several studies. This is particularly the case if these costs are later compensated for through lower energy consumption. This, too, will promote the trend toward lightweight design [27].

Another common insight of the benchmark is that by using the latest steel materials and forging technology, the costs per kilogram lightweight design even lies below that incurred for some more recent types of technology. And what is more, some lightweight design potential even promises cost neutrality. Overall, the results verify both quantitatively and, above all, qualitatively the sheer power of innovation demonstrated by steel manufacturers and forging companies [29].

Future activities of The Lightweight Forging Initiative will include continuous communication of the results at symposia and conferences of the automotive industry. This will also encompass regular lecture events to present the results of the participating companies in greater detail and to discuss lightweight design potential directly with a large number of experts.

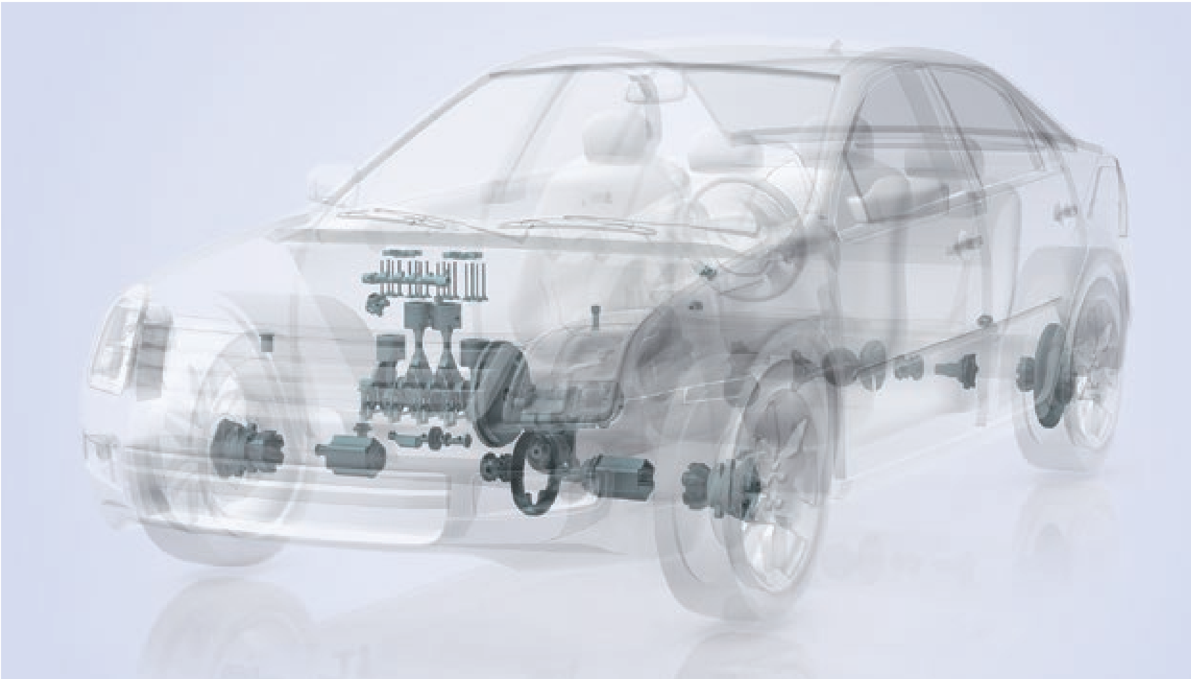


Figure 52: Lightweight design potential of forged components in cars

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