Lightweight potential for a light commercial vehicle

The Lightweight Forging Initiative has, during phase I, demonstrated a lightweight design potential of 42 kg in the powertrain and chassis of a passenger car. This successful undertaking is now being continued in Phase II in the light commercial vehicle segment (“Light Duty Truck” according to American standards). A vehicle was dismantled at fka Aachen and all the components were documented. In hands-on workshops, material, forging and conceptual lightweight ideas were generated. During Phase II, greater focus is being placed on materials compared to the first phase. A study at IPEK – Institute of Product Engineering at Karlsruhe Institute of Technology (KIT) analysed the quantitative lightweight potential of stronger steels for transmission applications. This makes it possible to quantify the cost of lightweighting using stronger transmission steels.

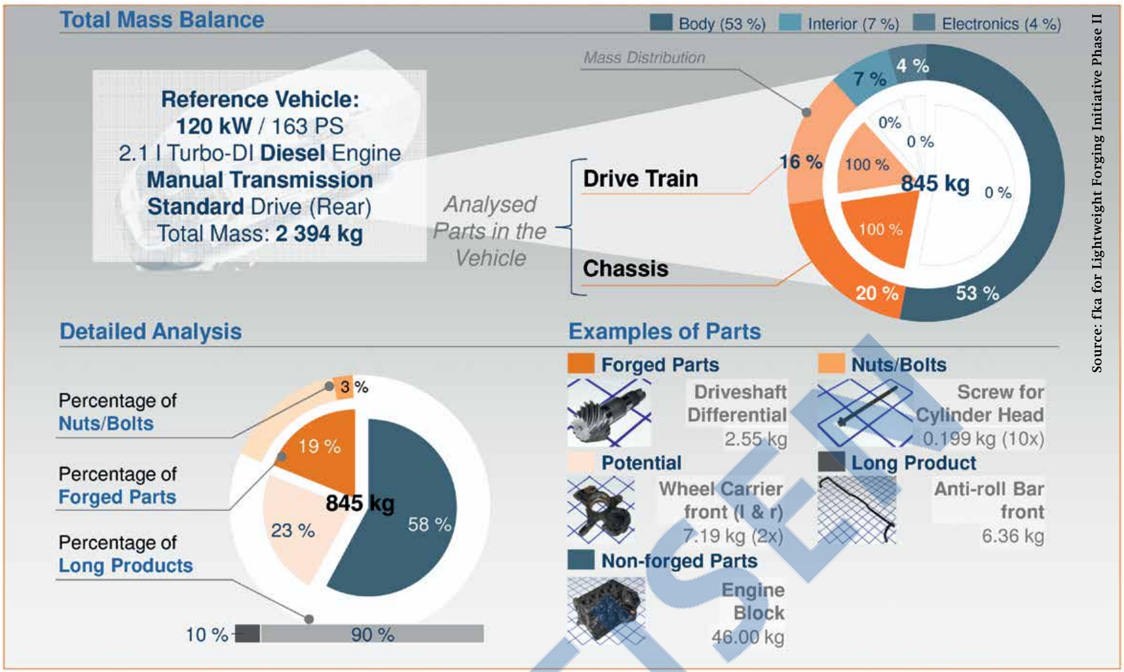
Hans-Willi Raedt, Frank Wilke and Christian-Simon Ernst

The Lightweight Forging Initiative was formed in 2013 by 15 forging and nine steelmaking companies under the auspices of the German Forging Association (IMU) and the Steel Institute VDEh. During Phase I, a medium-size passenger car was analysed and a lightweight potential of 42 kg was identified for components in the powertrain and chassis [1]. Based on the tremendous interest that the results received from customers and driven by the intensive cooperation within the two participating industries, a decision was made to launch Phase II in 2015 to focus on the lightweight potential of forgings in a light commercial vehicle. Phase II of the Lightweight Forging Initiative brings together 17 forging companies, ten steelmakers and one engineering service supplier, figure 1.

Lightweight potential in a light commercial vehicle

The vehicle. In the first phase of The Lightweight Forging Initiative, a medium-sized passenger car was analysed. During the second phase a light

1 The Lightweight Forging Initiative – status in summer 2015



2
Analysis of the Light Duty Vehicle. Weight distribution of systems and manufacturing processes within the LDV

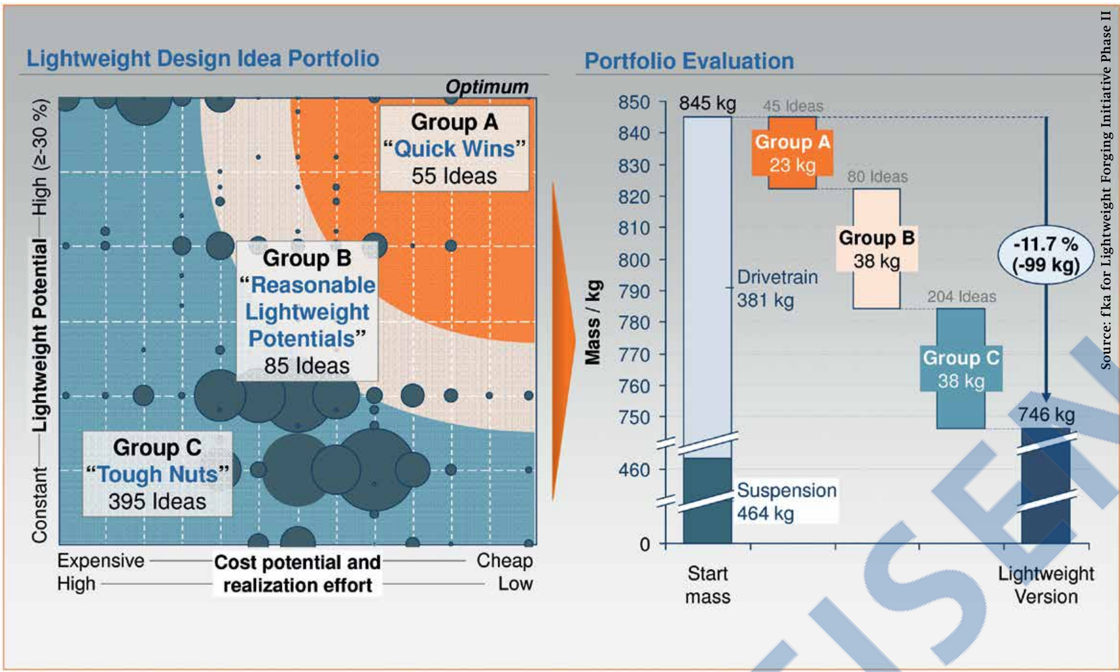
commercial vehicle (LDV) will be analysed for lightweight potential with forged components. In contrast to cars, the weight of LDVs continues to increase from one generation to the next. However, the stipulations for decreasing CO_2 emissions in cars likewise apply to LDVs. Exceeding CO_2 emissions will be penalized. It should also be noted that the total cost of ownership is more critical in commercial vehicles than in cars – lightweighting leading to the reduction of fuel consumption has a bigger impact on purchasing decisions than in passenger cars [2].

1.44 million light commercial vehicles (from car size up to 3.5 t) were sold in the EU in 2013. The vehicle chosen for this lightweight design potential analysis is very representative for this class. For this vehicle, legislation requires a reduction in CO_2 emissions of 13 % to stand at 182 g of CO_2/km by the year 2020. The vehicle has a 2.1 l, four-cylinder, 120 kW diesel engine, a manual 6-speed transmission and rear wheel drive, thus representing the most widely sold configuration.

Of the total mass of 2 394 kg the powertrain and chassis contribute 845 kg. These two subsystems will be the focus of further analysis for lightweight design potential through forging. The drivetrain weight of 383 kg is dominated by the internal combustion engine. The chassis has a weight of 479 kg. The weight distribution between the front and rear axle is quite balanced. The analysis by production processes shows that forged components (including fasteners, nuts and bolts) make up 19 mass percent of the drivetrain and chassis, figure **2**. About 10 % of the 845 kg in the drivetrain and chassis are long products that are not forged (tubes, springs, etc.). Any weight saved in the vehicle will allow for a higher payload.

„Even though forging and steel production technologies have been in use for a long time, there are continuous improvements in this field. Established and standardized steel grades are permanently optimized“

The procedure. The same procedure was used for generating ideas for lightweight potential as in the first phase of The Lightweight Forging Initiative [1]. After finding a representative model for this application segment, the vehicle (ensuring it was the latest generation) was purchased second-hand (age: 12 months, mileage: 23 000 km). This not only reduced lead time, but it also allowed the participating steel producers and forging companies to gain an impression of the load on the parts by observing wear marks. The vehicle was then dismantled. Every component in powertrain and chassis was documented (weight, photos from different perspectives, including the assembly position, material and manufacturing process) before being stored in a database. Two hands-on workshops then took place in which the members of the initiative analysed all 2 536 parts and generated lightweight potential ideas. The ideas were classified according to weight reduction potential, possible impact on manufacturing cost and finally according to the level of implementation difficulty.



3
Overview of the three categories of ideas for lightweight potential and their effects on lightweighting

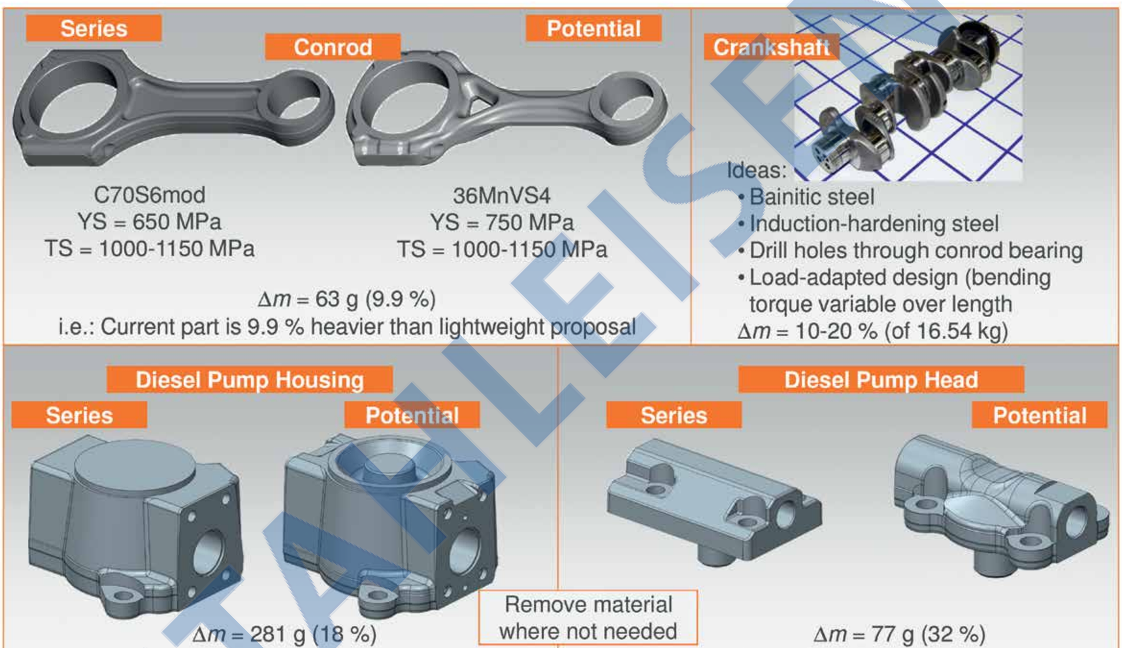
Ideas for lightweight potential. Five hundred and thirty-five ideas for lightweight potential were generated in total. With the classification data attributed to each idea, an overview for a meaningful prioritization of lightweight suggestions can easily be generated. The ideas may be grouped into three categories in a portfolio chart, figure 3. On the x-axis the ideas have been placed with cost impact vs. realization potential with respective impact factors 2 : 1. On the y-axis, the lightweight potential is shown. The first category of ideas is the "Quick Wins". These ideas should be pursued fast and with high priority. They offer a decrease in weight with no or hardly any cost increase and pose no or only little implementation difficulty. The Lightweight Forging Initiative, however, clearly wants to state that this is not at all meant as criticism towards the designers at the manufacturer of the vehicle. The second category encompasses those ideas with "Reasonable Light Weight Potentials". They offer weight reduction at increased cost and require greater implementation efforts. It should be noted that these efforts need to be compared thoroughly with those involved in the other lightweighting options in a vehicle, which are currently dominating the headlines (CFC, sheet-metal steels, plastics). Forging is a proven technology and can offer a better lightweighting cost per kilogram of weight saving than many other manufacturing methods – if given the appropriate attention (which is one of the primary goals of The Lightweight Forging Initiative). The third category is the group of "Tough Nuts". Here, cost and effort increase further. However, these may still be attractive if all options for lightweighting need to be exploited. The size of the bubbles in figure 3 represents the number of ideas for this point in the portfolio space.

For the whole vehicle, weight savings of 99 kg in total were identified on the basis of the lightweight design potential which may be achieved through forging, alternative materials or lightweight concepts. Implementing the best lightweight proposals would mean that the weight of the powertrain and chassis in this vehicle could be reduced by 11.7 % (or: the original system is 13.3 % heavier than the lightweighted system).

In the following sections, some ideas for lightweight potentials will be presented in order to demonstrate the impact of material and forging technology on component and system weight. The weight savings quoted as a percentage always refer to the percentage by which the series component is heavier than the lightweight suggestion.

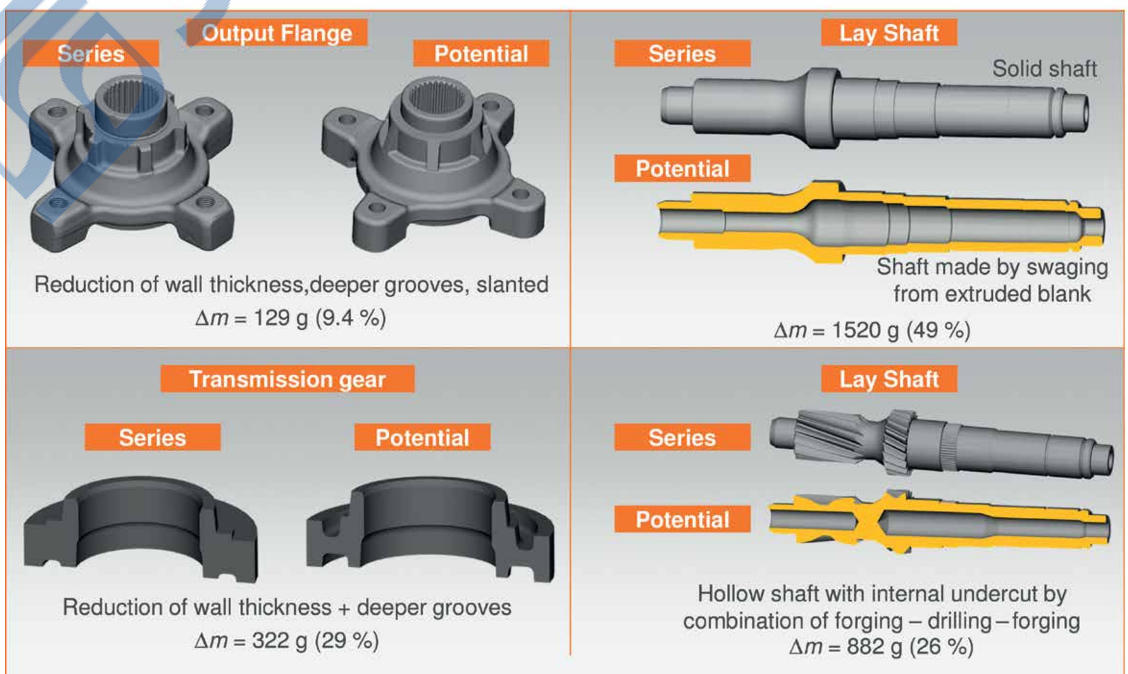
Engine. The engine is placed directly on the front axle and, together with the transmission, contributes significantly to the mass of the vehicle. Its components are subjected to high stresses and ultra-high fatigue cycles. Nevertheless, weight savings are possible on these parts. Figure 4 shows a few examples of lightweight suggestions. Conrods in combustion engines exhibit a similar shape in nearly all engines worldwide. Recently, new geometries have been proposed by different sources with the aim of reducing weight while retaining comparable levels of stiffness and resistance to buckling load and stresses. Together with improved materials, these geometries may lead to a 10 % reduction in conrod weight. The crankshaft is one of the single heaviest components in the engine. Improved steel materials and geometrical optimizations — and particularly the combination thereof — could lead to a significant reduction in weight. In the fuel injection system, the diesel pump housing as well as the high-pressure pump head may shed some weight through exploiting the full potential of the free shaping possibilities provided by forging technology. Although not shown in figure 4, it is worth mentioning that the common rail in this vehicle could shed 239 g, rendering the series part 27 % heavier than the lightweight version. This is possible by designing the rail not as a cylinder with additional geometries for function but as a free shape with varying diameters. The part exhibits the same maximum stresses at the most highly loaded points as in the current version.

Transmission. The manual transmission in this vehicle has a total mass of 60.8 kg. The forged components in this system contribute nearly 22 kg to



Source: Schmiedetechnik Plettenberg, ArcelorMittal, Saarstahl, Georgsmarienhütte, Linamar Seissenschmidt Forging, sachs engineering, Hirschvogel Automotive Group

4
Ideas for lightweight design potential in the fuel injection system and engine



Source: Hammerwerk Fridingen, Felss Group, Hirschvogel Automotive Group, Linamar Seissenschmidt Forging

5
Ideas for lightweight design potential in the manual transmission

this. Thus, weight savings in the shafts, gear wheels or in the output flange can lead to a significant decrease of system mass, figure 5.

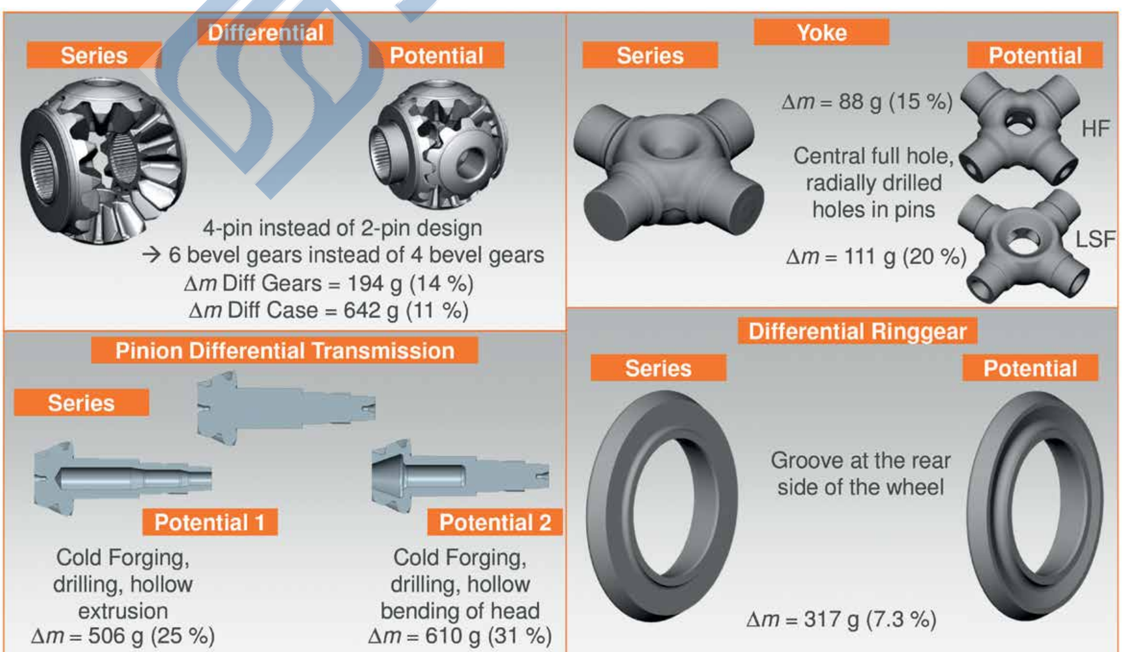
The output flange in the vehicle already exhibits some intricate shapes for the purpose of achieving weight savings. Nevertheless, deeper grooves and additional slanted sides would also assist in removing some mass, figure 5. The shafts lend themselves to hollow design. This can either be fulfilled with swaging technology, starting with tube material or an extruded blank. An alternative hollow manufacturing method would be cold forging, drilling and subsequent hollow extrusion, allowing for an internal undercut, too. It becomes apparent that very different manufacturing processes can lead to a reduction in mass. Ultimately, the final weight, the manufacturing costs and the total material input (if resource efficiency is to be assessed) will be taken into account in order to make the final manufacturing choice. Another lightweighting idea in the transmission system addresses the gear wheels, which are mostly rotational symmetric here. With these parts, smaller wall thicknesses and deeper grooves, which can be forged, lead to significant weight savings on the component.

Downstream powertrain. From the output of the transmission to the input into the driven wheel hub there are many components transmitting torque. Achieving weight savings with these components reduces the mass that is accelerated translatorically. However, in transmission and powertrain, their rotational inertia may not be neglected either – reducing mass here thus contributes two-fold in the reduction of fuel needed for driving.

In the differential transmission, the bevel gears form the central subsystem, which are now mostly net shape forged. One suggestion is to move from a two- to a four-pin subsystem, increasing the number of bevel gears by two. Due to lower loads per tooth, the total weight of the bevel gears can be reduced by 194 g. As a result of reduced assembly space, the size and weight of the housing can be reduced, too, with an expected weight reduction of 642 g, figure 6. Depending on torque load, the weight of the spider inside the cardanic yoke can be reduced by introducing a central hole as well as by radially drilling through the pins. The ring gear in the differential transmission can lose some weight by introducing a forged groove on the rear side while still leaving sufficient material below the teeth. Finally, the pinion can be made partially hollow. The combination of forging and machining technologies allows different solutions which lead to varying levels of weight reduction and which can take the subsequent clamping/machining concepts on the customer side into account.

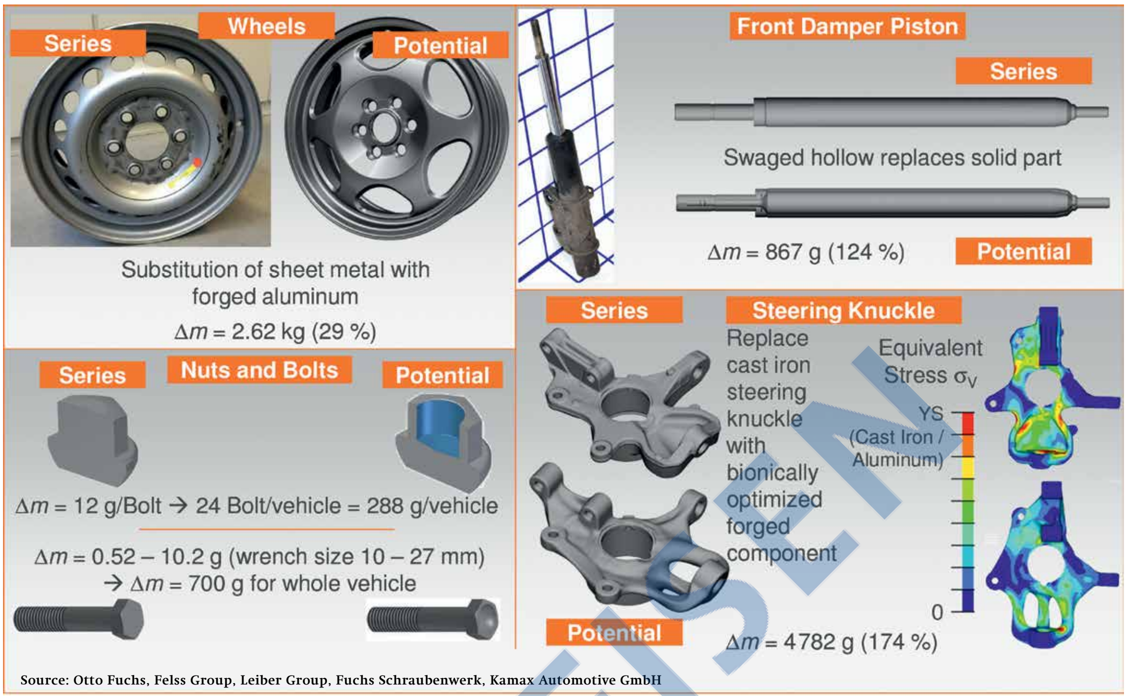
In the propeller shaft, too, a remarkable lightweight proposal was put forward for a subsystem design. The idea involves replacing the conventional splined hub/shaft connection with a Hirth gear on both parts (yoke/flange). This could lead to a significant reduction in weight due to saving material at a considerable distance from the rotating axis and due to the possible removal of some nuts and bolts.

Chassis. The chassis carries the vehicle and is designed as a safety-critical system. As the chassis has a considerable amount of unsprung mass, lightweight design is especially beneficial here.



Source: Metaldyne, Hammerwerk Fridingen (HF), Linamar Seissenschmidt Forging (LSF), HAY|GROUP, Hirschvogel Automotive Group

6
Ideas for lightweight design potential in the powertrain



7
Ideas for lightweight design potential in the chassis — mostly front axle

Forged aluminum wheels can replace the coated sheet-metal wheels used currently. The forged wheels made from EN AW 6082 in the T6 heat treatment condition exhibit a yield strength (YS) of 330 MPa and a tensile strength (TS) of 360 MPa with good ductility. The proposed Al wheel was designed for a wheel load of 975 kg, figure 7. Today, forged aluminum wheels are mostly found in luxury segment cars — and in the BMW i3 for extreme exploitation of lightweight design. However, as forged aluminum wheels represent a very efficient solution for lightweighting in the chassis, it is to be expected that they will penetrate the market downwards.

The front damper system of the axle features a solid damper piston. The suggestion to replace this piston with a swaged hollow version can reduce the weight by more than 50 %. Another material substitution is suggested for the steering knuckle. This involves replacing cast iron (YS 250 MPa, TS 400 MPa) with forged aluminum (YS 360 MPa, TS 400 MPa). After bionic optimization (topology optimization and linear elastic FEA against material yielding), the current part is 174 % heavier than the lightweight suggestion.

Nuts and bolts are omnipresent throughout the vehicle. Optimizing these parts yields only a few grams each. However, multiplied with their huge number, a significant weight saving can be achieved. This applies to the bolts for fastening the wheels onto the braking disc and wheel hub. Here, the total number of bolts is only 24, yet the weight savings per part are fairly high at 12 g per bolt, which adds up to 288 g per vehicle. Another idea is a less pronounced dent in the head of the bolts which can be applied to bolts of all sizes. The weight saving per bolt is between 0.52 g and 10.2 g (for wrench sizes between 10 and 27 mm). The weight saving for the whole car is estimated at around 700 g for the whole vehicle at a cost increase of only around 5 % for the bolts. Additionally, in the whole vehicle only fasteners with a strength below the 10.9 class were found. Exploitation of the 10.9 strength class might yield even more lightweight potential.

The rear axle features a number of lightweight ideas, too. In the current configuration, a significant amount of weight is concentrated on the front axle, so achieving weight savings on the rear axle may not be top priority due to weight balancing. However, with the use of battery packs increasing even in the light commercial category, the weight saving pressure on the rear axle will increase in order to maintain a high payload.

Lightweight Forging Initiative

A success story in (currently) three chapters
Phase I: –42 kg in a passenger car
Phase II: –99 kg in a light commercial vehicle
▷ Design ideas
▷ Conceptual ideas
▷ Material-based ideas
Better steel yields cost-effective lightweight potential in the transmission
Large-scale research project with federal funding
▷ 10 institutes
▷ 59 companies
▷ From liquid steel to automotive systems

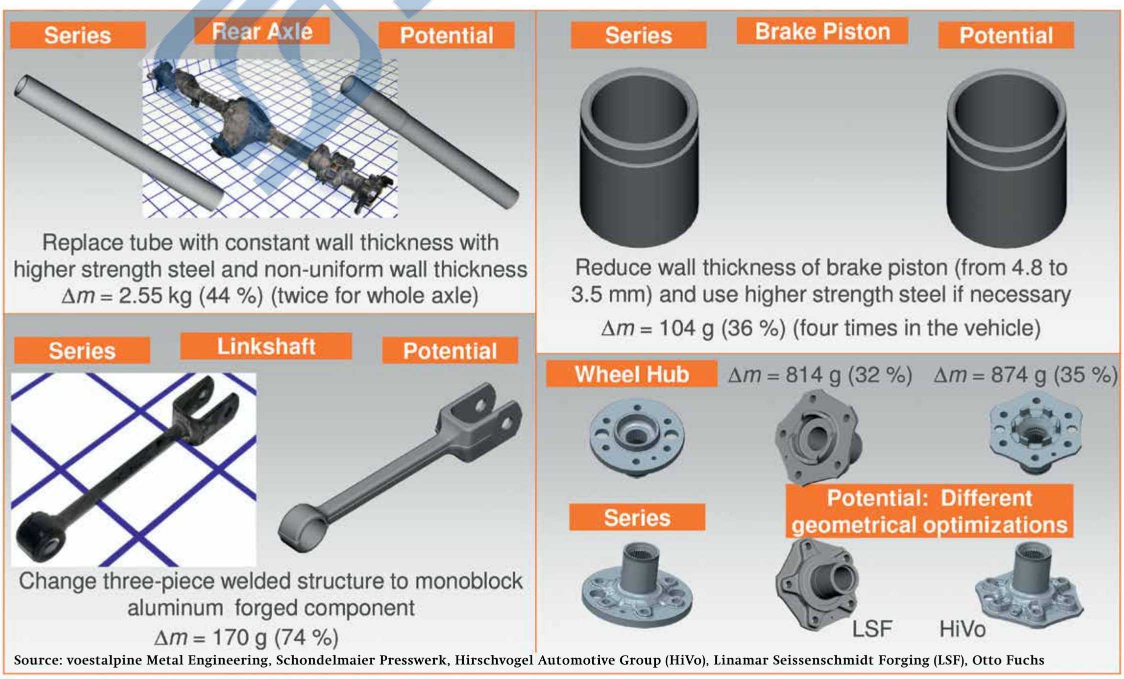
Figure 8 shows a few of the ideas for lightweight design potential with respect to the rear axle. Much of the weight of this subsystem stems from the tube connecting the differential transmission housing with the wheel carriers on both sides. Currently, this tube is made from St52 with a yield strength (YS) of 420 MPa. By changing the steel material to 20MnV6 with thermomechanical rolling, the YS increases to 600 MPa, allowing a reduction in wall thickness in non-welding areas. The current tube is 44 % heavier than the lightweight proposal. In the brake, the piston can be changed to a design with smaller wall thickness (from 4.8 to 3.5 mm). This can be achieved while still producing the ready-for-assembly outer and inner side by means of forging. This keeps manufacturing costs low and leads to an increase in the strain hardening of the steel. If this is not sufficient for the required strength, a slightly stronger steel can be used. For the four wheel hubs in the vehicle, different approaches are suggested, depending on the manufacturing possibilities of the respective suppliers. Generally, non-round, stiffness-optimized geometries prevail, rendering the current part more than 30 % heavier than the lightweight proposals.

At the bottom left in figure 8 again material substitution is involved. By changing a three-piece welded steel assembly into a monoblock aluminum forging, the steel part becomes 74 % heavier than the aluminum forging. The aluminum forging requires some machining steps but, in contrast to the steel part, welding and corrosion-protection processes can be omitted. The exact lightweighting cost would need to be determined in a more detailed study.

Lightweight potential with materials

Material developments in general. Even though forging and steel production technologies have been in use for a long time, there are continuous improvements in this field. Established and standardized steel grades are permanently optimized. Examples of such optimizations include better cleanliness to achieve better fatigue performance or improved testing methods to decrease possible defects. This measure reduces failure rates in components, thereby allowing for a more challenging design. Examples of this are already in series production. At the same time, new steel grades with improved properties are being developed, allowing for increased performance at a better ratio of performance versus cost [3]. A strong trend in the forging industry to date is the introduction of bainitic steels, which provide the strength of quenched and tempered steels with high cost efficiency due to the omission of the hardening process in favour of controlled cooling after forging.

The use of steels with higher strength might lead to lightweight potential in cases where overload or fatigue strength limits the design of the component. For these steel materials, the whole process chain needs to be re-evaluated, as processing issues in forging, machining and heat treatment need to be solved. Again, a good cooperation between the steel producer, processing companies and the end-user is necessary to successfully complete such developments. The fastener industries are currently intensively discussing the use of higher strength steels for bolts, particularly in the light of susceptibility to hydrogen-induced failure [4]. Steel wire producers and the fastener industry have by now deeply



8
Ideas for lightweight design potential in the chassis — rear axle

understood and eliminated the topic of hydrogen take-up for high strength steels during fastener production [7]. The lightweight pressure demands that already developed knowledge now finally finds its way into application, where currently over-cautious older standards reflect the state of the art dating back some decades.

„The transmission design model now makes it possible to analyse the influence of model input parameters (especially steel strength values such as the maximum permissible tooth flank stress, tooth root stress, torsional and bending stresses in the shafts, etc.) on the system weight“

Stronger steels — lighter transmission (and other gear applications). Steels in transmission applications have to withstand extreme loads. High contact pressure on the tooth flanks with additional sliding movement leads to a severe Hertzian stress field which may result in pitting fatigue on the flank. The tooth itself is subjected to a bending load which leads to tensile stresses in the tooth root. Carburizing is the most commonly used heat treatment process to withstand these loads. A wide range of carburizing steels is available, with low alloy grades offering basic performance. Higher alloyed grades are used in more demanding applications but lead to higher costs due to the surcharge for alloying elements such as molybdenum or nickel.

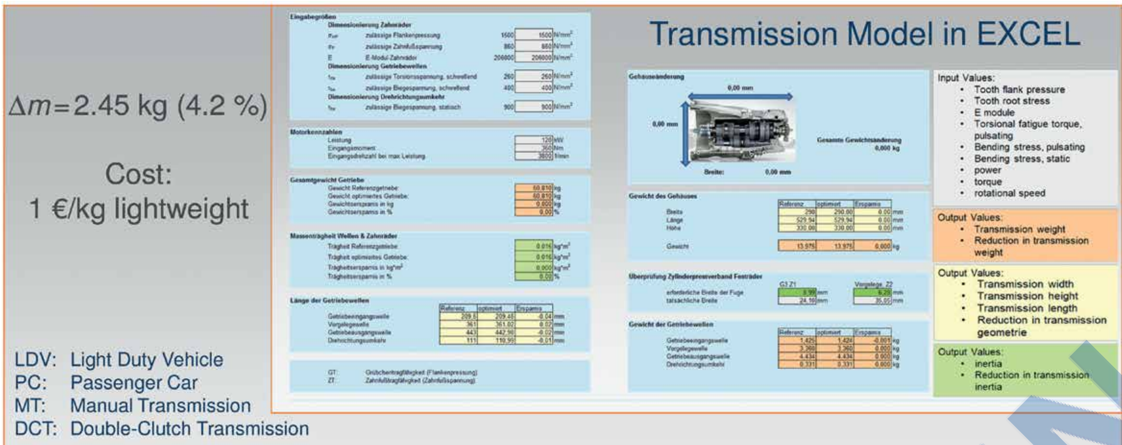
The call for lightweighting is increasing in the entire field of automotive technology. The Lightweight Forging Initiative thus considered it worthwhile to explore the relationship between the increased cost of using either alloying elements or more sophisticated steelmaking processes (in order to improve steel cleanliness) and the possible lightweighting of the transmission resulting from this. In order to do so, a transmission design study was commissioned at the Institute of Product Engineering (IPEK) at Karlsruhe Institute of Technology (KIT). The manual transmission of the light commercial vehicle is modelled in an Excel sheet. Following the German DIN 3990/ISO 6336 standard, the helical gears are designed against pitting resistance and tooth root strength. For shrink-fitted gear wheels, the torque transfer capacity is calculated according to DIN 7190. The transmission shafts are designed against fatigue according to DIN 743. Based on fixed input values (engine power, speed and torque) and on the transmission topology, it is now possible to vary the input values of pitting resistance and tooth root fatigue strength. Depending on the increase in these strength properties, the model can predict savings in system weight and size, figure 9. To calculate weight reduction, the decrease in size of the gear wheels and shafts is directly taken into account. An additional assumption calculates the secondary weight effects within the shrinking transmission housing. The synchronization subsystem and the actuator system is not taken into account for weight savings. With design parameters taken from the above-mentioned DIN 3990 / ISO 6336 standard and through reasonable usage of strength values as suggested by FVA [6] for the medium alloy steel used here, the transmission design model calculates the weight of the transmission analysed in our light commercial vehicle with a high level of accuracy.

This transmission design model now makes it possible to analyse the influence of model input parameters (especially steel strength values such as the maximum permissible tooth flank stress, tooth root stress, torsional and bending stresses in the shafts, etc.) on the system weight. It thus becomes very easy to evaluate weight benefit against additional steel material cost.

In order to do so in a realistic way, a similar model has been created for a double-clutch transmission of another carmaker (from The Lightweight Forging Initiative Phase I [1]), which features a high alloy carburizing steel. Again, the model represents the transmission weight and size fairly accurately.

Now the strength values of the high alloy carburizing steel used in the double-clutch transmission are entered into the model of the manual transmission of the light commercial vehicle. This results in predicted weight savings of 2.45 kg. If the manual transmission were to be equipped with the high alloy steel found in the double-clutch transmission, it would be necessary to switch around 21 kg of shafts and gear wheels to the higher alloyed steel. This is without taking any other practical issues into account, such as release of material, change of heat treatment process or testing, etc. The higher alloy steel exhibits an increased material price (base price plus largely the alloy surcharge) of around 200 €/t (as of summer 2015). Given a certain loss between input weight (before the forging processes) and final component weight, it can be estimated that, for the whole input material the cost would rise by around 5 €. In other words, at an increased steel cost of

„In order to deepen and intensify the field of lightweight forging, a federally funded research project with ten research institutes and 58 participating companies started on 1 May 2015“



Vehicle	Flank Pressure Strength, MPa	Tooth Root Strength, MPa	Pulsating Torsional Strength, MPa	Pulsating Bending Strength, MPa	Weight, kg
LDV – MT Series	1500	860	260	400	60.81
PC – DCT	1510	950	410	850	64.3
LDV – MT Potential	1510	950	410	850	58.36

Source: IPEK — Institute of Product Engineering at Karlsruhe Institute of Technology (KIT), Lightweight Forging Initiative

9
Stronger Steels — Lightweight in Transmission. Transmission design model implemented in Excel

5 €, the transmission could lose 2.45 kg, representing weight savings of 2 €/kg.

If we now assume that the input weight for the forged components drops by the same amount of 2.45 kg, a cost of around 3 € in base price and alloy surcharge could be saved, leaving a total cost increase of 2 € for the lighter transmission. It can thus be assumed, that a weight saving of 2.45 kg may be achieved at an increased cost of less than 1 € per kg of weight saved. Saving weight by using more sophisticated steels in transmission applications is thus a very cost-effective lightweight measure. This not only applies to the transmission itself, but to all systems where gears mesh (differential transmission, transfer boxes, etc.).

Conclusion and outlook

The Lightweight Forging Initiative has demonstrated on two different vehicles (passenger car and light commercial vehicle) that modern forging materials and forging technology can significantly contribute to lightweighting efforts in the automotive industry. In its second phase, the importance and effectiveness of high quality steel in transmission applications has been more intensively highlighted.

The optimum combination of component design, materials and manufacturing technology ensures the development of a high quality lightweight solution in mass production and at a competitive lightweighting cost.

In order to deepen and intensify the field of lightweight forging, a federally funded research project with ten research institutes and 58 participating companies started on 1 May 2015. The project focusses on the development and validation of high strength steels, on new forging methods as well as on the difficulty of implementing lightweight ideas in a manufacturing chain involving many partners. Within the next three years many more ideas can be expected to come out of The Lightweight Forging Initiative [8].

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