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April 2017

Body development at Audi – innovation, quality and precision

Automotive lightweight design – triumph of an idea

Audi is writing a new chapter in its successful history of lightweight design. For the coming generation of the Audi A8, an intelligent mix of four materials will be used in the body structure for the first time – more than in any of the brand's previous production models. The luxury sedan is thus once again rightfully claiming its role as an innovation driver in automotive lightweight design. A tradition that dates back to the year 1994, when the A8 with its aluminum unitary body in Audi Space Frame (ASF) design caused quite a sensation.

Audi long ago abandoned the obsession with using a single material, however. In modern lightweight design the focus is on intelligent and flexible use of a wide variety of materials – in keeping with the principle "the right material in the right place in the right amount". Each material is tested to determine its suitability for its intended purpose, and the Audi experts possess an in-depth understanding of its potential and the advantages it offers. All advances in the "competition of materials" can be put to direct use by the company in its new models.

This constantly growing wealth of know-how is particularly evident in the coming generation of the Audi A8. The luxury sedan's load-bearing structure combines four different lightweight design materials – a mix of aluminum, steel, magnesium and carbon fiber-reinforced polymer (CFRP). It has thus ushered in a new stage in multi-material construction that provides direct benefits to the customer – and not only in terms of weight. As for torsional rigidity – the critical parameter for precise handling and pleasing acoustics – the new Audi A8 surpasses its outstanding predecessor's rigidity value by up to 24 percent.

Ever since the first generation of the Audi A8, the Audi Space Frame (ASF) has been generating strong momentum for lightweight design in automobiles. Since then the premium brand has built more than one million production cars in accordance with this design principle, and it has been consistently building upon its know-how in the use of materials and joining techniques. The result is bodies whose low weight and high rigidity form the basis for greater performance, efficiency and safety.

Following nature's example – the Audi Space Frame design principle

"The decisive inspiration for the Audi Space Frame is found in nature," said Dr. Bernd Mlekusch, Head of the Audi Lightweight Design Center (ALC) in Neckarsulm. "In a bee colony, for example, only the amount of material required to serve its function is used." In the early 1990s the lightweight design experts at Audi drew from this insight when they were designing the structure of the ASF, which consisted of extruded profiles and die-castings. Sheet panels including the roof skin, floor and side panels were incorporated into this lattice to boost rigidity and serve a load-bearing function. The individual components exhibit various shapes and cross-sections depending on their task.

The aluminum ASF body of the first A8 generation made the car more than 40 percent lighter than had been possible with a conventional steel design. That kicked off a development spiral among the steel producers in the competition of materials. Since then, the strength of new high-strength steels has increased by a factor of five.

And of course the ASF aluminum technologies didn't remain static. They were always being further developed in the direction of new material grades and joining technologies, which are available on the market today. This is why the Audi lightweight design offensive has benefited not only the brand's own customers, but also the entire automobile industry.

The Audi Lightweight Design Center
The great expertise in body development that Audi has at its disposal has all been brought together in one location – the Audi Lightweight Design Center, which was established in 1994. What has been learned here has provided the basis for hundreds of patents, for being honored as 2008 European Inventor of the Year by the European Patent Office, and for winning the Euro Car Body Award four times, the leading competition in the field of car body manufacturing.

Among the roughly 200 specialists at the ALC, about 25 experts are concentrating on fiber-reinforced polymers (FRP). The FRP Technical Center covers the development process in its entirety. The center focuses on not only materials technology, but also the full spectrum of expertise in component processes technology, development of new joining technologies, quality assurance and development of service and repair solutions.

An intelligent mix of materials – the body of the new Audi A8

For the next generation of the A8, Audi is employing an intelligent mix of four materials in the body structure for the first time, and the new flagship model's low weight and high rigidity are the basis for greater performance, efficiency and safety.

The experts at Audi long ago abandoned the obsession with using a single material in lightweight design. With a mix of aluminum, steel, magnesium and carbon fiber-reinforced polymer (CFRP) they are establishing a new level in multi-material construction of the Audi Space Frame (ASF) for the next generation of the A8 – in keeping with the principle "the right material in the right place in the right amount".

The company consistently applies new material technologies and designs that are directly beneficial to the customer – and not only in terms of weight. The upcoming flagship's torsional rigidity – the critical parameter for precise handling and pleasing acoustics – surpasses its predecessor model's rigidity value by up to 24 percent.

Innovative production process: The carbon rear panel in the new Audi A8
In terms of its overall dimensions, an ultra-high-strength, torsionally rigid rear panel made of CFRP is the largest component in the occupant cell of the new Audi A8, and it contributes 33 percent to the torsional rigidity of the total vehicle. To optimally absorb longitudinal and transverse loads as well as shearing forces, between six and 19 fiber layers are placed one on top of the other, ensuring a load-optimized layout. These individual fiber layers consist of tapes 50 millimeters *(0.2 in)* wide and can be placed individually in a finished layered panel, with any desired fiber angle and minimal trimming of the fibers. The innovative direct-fiber-layering process specially developed for this purpose makes it possible to entirely dispense with the normally needed intermediary step of manufacturing entire sheets of carbon fiber. Using another newly developed process, the layered panel is wetted with epoxy resin and cured within minutes.

A high-strength combination of hot-formed steel components make up the occupant cell, which comprises the lower section of the front bulkhead, the side sills, the B-pillars and the front section of the roof line. Some of these sheet metal blanks are manufactured in varying thicknesses by means of tailoring technologies – they're tailor-made in other words – and others also undergo partial heat treatment. That reduces weight and increases the strength, especially in areas of the vehicle that are particularly critical for safety.

Aluminum components in the form of cast nodes, extruded profiles and sheets, elements characteristic of the ASF design, make up the biggest share of the new Audi A8 body, at 58 percent. And here too the competition of materials has been driving progress. New heat-treated cast alloys, for example, attain a tensile strength of over 230 MPa (megapascals). The corresponding yield strength in the tensile test is over 180 MPa, and for the profile alloys it is higher than 280 and 320 MPa – significantly higher values than seen previously.

Rounding out the intelligent mix of materials is the magnesium strut brace. A comparison with the predecessor model shows that it contributes a 28-percent weight saving. Aluminum bolts secure the connection to the strut tower domes, making them a guarantor of the body’s high torsional rigidity. In the event of a frontal collision, the forces generated are distributed to three impact buffers in the front end.

Benefits for customers and the environment – the new body shop for the Audi A8
In addition to the complete redevelopment of the Audi Space Frame for the next generation A8, the production halls at the Neckarsulm location were specially built for the upcoming flagship. A total of 14,400 metric tons of steel were needed just for construction of the new, 41-meter-high body shop, twice as much steel as was used for the Eiffel Tower in Paris.

In 1994 it was the first generation of this luxury sedan, with its aluminum unitary body, that made the Audi Space Frame an established presence in the automotive world. Since then the company has built more than one million production cars in accordance with this design principle, and it has been continually building upon its know-how in the use of materials and joining techniques. The result is innovative bodies whose low weight and high rigidity form the basis for greater performance, efficiency and safety.

The body shop – 14 joining processes
Along with expanding the mix of materials, Audi consistently focuses on innovative production technologies. The brand is using 14 different joining processes to assemble the multi-material body for the new A8, including roller hemming, grip punch riveting, and remote laser welding of aluminum which is being done here for the first time anywhere in the world.

Roller hemming is used all the way around the complete front and rear door cutouts on the new Audi A8. Thanks to the design made possible by this technique, getting in and out of the car will be even more comfortable and the driver’s field of vision will be wider around the A-pillar, an area that is critical for save driving. It also enabled the engineers to gain up to 36 millimeters *(1.4 in)* at the door cutouts compared to the predecessor model.

The grip punch riveting, which fixes the side wall frame in its position, accompanies the roller hemming process, which in turn is supported by structural bonding. It was the development and adaptation of these joining technologies to this specific application that first made it possible to use the material concept in the new A8, and to combine the aluminum side wall frame with the hot-formed, high-strength steel sheets at the B-pillar, the roof line and the sills with their thin flanges.

With remote laser welding of aluminum, Audi has developed a new approach realized by no other premium automaker. Exact positioning of the laser beam in relation to the welding edge considerably reduces the risk of hot cracking because the heat input can be precisely controlled. The size of the gap between parts being joined can immediately be determined and effectively filled in by means of process control strategies. The laser beam's high feed rate and low energy use reduce CO_2 emissions by about one quarter. This new process also results in a 95-percent saving on recurring costs in series production because it eliminates the need for the costly process controls required with conventional laser welding.

Used in the rear of the new A8 – at the water drain channels – is a further development of the conventional aluminum MIG (metal inert gas) welding process based on the established CMT (cold metal transfer) process. The development approach is essentially a geometric modification of the inert gas nozzle, which makes it possible to achieve process speeds of up to 50 mm/s and a very fine weld seam appearance. Compared to the conventional MIG welding process, this corresponds to a threefold increase in speed for equivalent applications in the body shop. This improvement also results in considerably reduced heat input, and therefore also less risk of component distortion. To ensure the welding wire is positioned at the component edge with the required precision, the process is performed in combination with a system for automatic seam detection and seam tracking.

Resistance spot welding (RSW) of aluminum is a highly versatile joining process. Here too, high-performance plant technology combined with control technology adapted to the requirements of working with aluminum are delivering improvements in process stability and reproducibility of welding results. Use of welding tongs with higher electrode forces makes it possible to reduce undesirable adhesions from the copper electrode onto the aluminum component.

Laser welding – a classic Audi highlight in the body shop – is used to join the sides of the A8 roof to the side walls along a practically invisible zero gap.

The new Audi A8 body shop at the company's Neckarsulm plant

Audi is building the Space Frame for the new flagship A8 in a newly erected building at the Neckarsulm plant that is full of very sophisticated technologies. The highly automated production flow in the plant is very complex yet also efficient.

The entire A8 body shop was designed to ensure maximum energy efficiency and conservation of resources. The new spot welding tongs are powered by electric motors, and they weigh 35 kilograms *(77.2 lb)* less than their predecessors – allowing Audi to deploy smaller robots, which in turn use less electricity. The halls are equipped with LED lighting, and intelligent concepts for ventilation and shutting down equipment further reduce energy requirements.

The plant is equipped with about 500 robots, 90 adhesive systems, 60 machines for self-tapping screws, 270 punch riveting systems and 90 resistance spot welding tongs. Many robots perform several process steps, and in the intervals they autonomously switch to the tools needed, such as gripping arms and adhesive guns.

A total of 14,400 metric tons of steel, twice the amount used for the Eiffel Tower in Paris, and more than 16,000 loads of concrete – the body shop for the next Audi A8 has taken shape as an all-new production site. In the plan view, the two directly adjoining buildings resemble an equilateral triangle.

There are three production levels in the new building, which is 41 meters *(134.5 ft)* high. Each level encompasses 50,000 square meters *(538,195.5 sq ft)* of floor space, the equivalent of seven soccer fields. Supporting columns divide the floor space of each level into a grid of 500-meter *(1640.4 ft)* sections. Beneath one of the halls is the plant's railway loading station, where girders span a distance of 36 meters *(118.1 ft)* over the rail tracks. The column that bears the heaviest load must support a weight equivalent to that of 1,800 Audi A8 models. At times, 17 cranes were in operation simultaneously during construction, including two of Europe's biggest tracked cranes, each capable of lifting up to 600 metric tons.

From the longitudinal member to the roof: The superstructure of the ASF body
The ASF body's superstructure begins with the lower welded assemblies, which include the longitudinal members. They form the foundation for the front and rear body modules. The latter is produced on a separate level of the building. In the next step, the two subassemblies are merged with the floor panels.

The occupant cell takes shape on this underbody, starting with the A-, B- and C-pillars, then the internal and external side panels, and on to the installation of the roof. The big steps take place in the geometry and framing stations, where the parts are positioned and aligned for the welding process with utmost precision. The body shell moves on a conveyor into the adjacent building, where it is fitted with its doors and lids, which have been produced there in advance. After the body has proceeded through the finishing line on the level below, it is transported to the adjacent paint shop. And following cataphoretic painting, the metal ASF cures in an oven at 200 degrees Celsius, where the aluminum alloys reach their final strength.

Inline laser measuring equipment checks the dimensional accuracy of the ASF body at 20 stations during its creation – the first station examines the rear module substructure, and the final station the finished superstructure. Above and beyond these measures, Audi Quality Assurance conducts spot tests of individual components, subassemblies and even complete bodies. And a new measurement center has been set up next to the line for that purpose.

The tools Quality Assurance uses include two coordinate measuring machines, which work with tactile and optical sensors, an ultra-high resolution optical measuring cell, an ultrasound imaging system and a large computer tomograph (CT). Ultrasound imaging and CT enable the specialists to test many joints in the body without having to take them apart. Traditional destructive testing methods and auditing of surfaces round out the spectrum.

The CFRP rear panel: Installation in the final assembly area
The CFRP rear panel is installed in the car during final assembly – already fitted with all components and subassemblies, including the loudspeakers, the rear louver, the three-point seat belts and the center armrest.

A robot uses a handling device to pull the rear panel through the rear window cutout and into the body. A two-component structural adhesive for preventing contact corrosion is used in conjunction with manually installed rivets to join the rear panel to the metal components.

Better qualified than ever: The employees
About 500 people working in three shifts are employed in the new A8 body shop, which involves a high degree of automation. Most of them work in the automated area together with robots, and others in the manual area on the bolt-on and finishing lines.

To ensure a smooth production start for the new model, with its many upgrades, Audi has further expanded its training concept. Audi is training the employees well in advance for the start of series production, with special courses and advanced instruction emphasizing practical, hands-on learning. Depending on the specific type of qualification and the technology involved, a course on automation takes up to ten days.

A new element and special feature of the training concept, something not found anywhere else in the Volkswagen Group, is the finishing booth. The focus here is on working with the material aluminum, which requires great finesse.

The Audi Space Frame technology – milestones since 1994

Lightweight design has been a driving force at Audi for many years. The brand has been building cars with the Audi Space Frame (ASF) body continuously since 1994. And over the years it has time and again precisely tailored and improved the technology for use with the various vehicle concepts and their new requirements – right up to the latest stage, the multi-material ASF.

The Audi A8 (1994)

For the first generation of the Audi A8, the company once again completely reinvented the unitary body – using aluminum as a material and a concept tailored to the lightweight metal. The development work, which got started in 1982, yielded 40 patent applications. In the role of the production model's forerunner was a technical study with the "ASF" designation, which caused a sensation at the 1993 IAA – its unpainted body of polished aluminum gleamed like silver.

The aluminum unitary body of the Audi A8, which followed in 1994, weighed only 249 kilograms *(549.0 lb)*. And it was endowed with the fundamental ASF design principle, which still applies today: Extruded profiles – many with closed multi-chamber profiles – formed a lattice together with complex die-castings. Aluminum panels gave the structure rigidity. Of the 334 individual components, they were dominant, making up 71 percent of the total mix and far surpassing the share of profile and cast components. Roughly 75 percent of the assembly work at the Neckarsulm plant was done by hand.

The Audi A2 (1999)

The Audi A2 was the second model from Audi in the ASF design – and the premium compact model stood out by virtue of its remarkably low weight. The base version had a curb weight (without driver) of no more than 895 kilograms *(1,973.1 lb)*, and the "3-liter" A2 1.2 TDI weighed in at just 825 kilograms *(1,818.8 lb)*. The key factors behind this were the Audi Space Frame and the aluminum add-on parts with a total weight of just 153 kilograms *(337.3 lb)*.

The A2 was conceived to be built in higher volumes than the A8, with up to 360 cars per working day. Its ASF showcased improvements and new developments that simplified the structure. The number of individual parts decreased to 225, and the B-pillar was made as a single large casting for the first time – for the luxury sedan it had still comprised eight components. Hydroforming was used to produce the profiles for the roof line, whose cross-section changed several times over its entire length. The underbody frame was welded together from extruded profiles, which were directly joined to one another.

The sheets also made up the largest share of the Audi A2 body, at 81 percent. Three joining processes dominated – punch riveting, MIG welding and the new laser welding, enabling Audi to achieve an 80-percent degree of automation.

The Audi A8 (2002)

For the second generation of the A8, the engineers improved the static torsional rigidity by 61 percent with the further developed Audi Space Frame, while the number of individual parts was reduced compared to the predecessor. The ASF body of the flagship model weighed only 220 kilograms *(485.0 lb)*, more than 40 percent lighter than equivalent steel bodies at that time.

Audi also achieved major advances with the large castings. Their share of the total weight of the ASF rose from 22 to 31 percent, and a few of them integrated new functions like the door hinge mounts in the castings of the A-pillars. As in the Audi A2, the big side wall frame from the A-pillar to the rear end was made of a single low-drawn aluminum sheet, although even considerably larger and more ambitious in the A8.

The joining techniques also were further optimized, and a new technology came into play – laser hybrid welding. This technology’s special strengths – minimal distortion, good performance when filling gaps, and high process speed – make it particularly well-suited for large component joints susceptible to distortion, like where the roof is joined to the side wall frame, to name one example.

The Audi TT (2006)

The TT of the second generation displayed a major new innovation from the brand – the multi-material Audi Space Frame. The front body module, middle floor and superstructure of the compact sports car are made of aluminum. As a result, the material accounted for 68 percent of the total weight of the coupé.

Steel was used for the rear section of the floor assembly, the rear end, and the bulkhead (on the roadster). And to ensure good weight distribution, the doors and the tailgate were also made of steel.

Compared to the predecessor model with its all-steel body, the new concept reduced the curb weight by up to 90 kilograms *(198.4 lb)*, depending on the version. In addition, it allowed outstanding axle load distribution and thus dynamic handling typical of a sportscar, bolstered by greatly increased torsional rigidity. The ASF body of the TT Coupé weighed only 206 kilograms *(454.2 lb)*. Aluminum’s share of the mix comprised 63 kilograms *(138.9 lb)* of sheet panels, 45 kilograms *(99.2 lb)* of castings and 32 kilograms *(70.5 lb)* of extruded profiles.

The Audi R8 (2007)
For its R8, Audi transferred the ASF concept to a high-performance sports car for the first time. The results speak for themselves: The body weight of the coupé was 206 kilograms *(454.2 lb)*. Extruded profiles play the lead role in the ASF sports car concept, at around 70 percent. Castings accounted for eight percent in the coupé, and aluminum sheets made up the remaining 22 percent.

And the ASF of the new Audi R8 also incorporated new ultra-lightweight materials. Made of magnesium, a rear cross-member in the engine compartment lent rigidity to the upper section of the rear module. For the Spyder, the rear side walls and the hood compartment cover – both load-bearing components – are made of carbon fiber-reinforced polymer (CFRP).

The Audi A8 (2010)
The third generation of the A8 – once again presenting impressive advances. Thirteen different grades of aluminum are used in the ASF, which is built from 243 individual parts. The B-pillars are made of ultra-high-strength, hot-stamped steel. The sedan body with the standard wheelbase weighs only 231 kilograms *(509.3 lb)*.

The composition of the Audi flagship's ASF works out to be 35 percent cast components, 35 percent sheets, 22 percent extruded profiles, and eight percent steel. Most of its cast components are made of improved alloys, produced using vacuum die-casting – a process that makes it possible to achieve mechanical properties with high values but also good ductility and good joining characteristics. For the higher strength components Audi increased the strength by up to 25 percent while also reducing the material thickness and the weight by up to 20 percent.

The Audi TT (2014)
With their multi-material design, the bodies of the current Audi TT and TT Roadster represent a new stage in the evolution of the ASF. The front end, and particularly the floor of the passenger compartment, contain many hot-formed steel components, which thanks to their extreme strength can perform with relatively thin walls, so they are lightweight. For the second time in a row, Audi succeeded in significantly reducing the curb weight of the TT while also increasing the torsional rigidity.

The characteristic ASF lattice of aluminum forms the superstructure of the occupant cell. Four castings comprise the nodes of the coupé – two at the A-pillars and two above the rear window – and the body, complete with the aluminum outer skin, weighs just 276 kilograms *(608.5 lb)*.

The Audi R8 (2015)
With the new R8, Audi once again lowered the ASF's weight, this time down to 200 kilograms *(440.9 lb)* for the coupé. The decisive factor behind this achievement is the new combination of aluminum and CFRP. The CFRP components – the rear wall, the center tunnel and the three-part B-pillars – are produced using the highly efficient resin transfer molding (RTM) process.

The dry fiber matting and local reinforcements are first laid down, formed and then inserted into closed, heated tools. After they are closed, liquid epoxy resin is injected into the form and completely soaks the matting – and the components are then cured under pressure and temperature. The CFRP components form the functional backbone of the ASF and account for a 13-percent share of the materials. Considered in detail, they serve a number of different purposes, which is why they vary greatly from one another in their number and arrangement of the webbing layers.

The front and rear body modules of the new R8 are constructed of aluminum – from semi-finished goods that include castings, profiles and sheets. Cast nodes make up 21 percent of the ASF, the extruded profiles account for a 47-percent share, and the sheet panels 12 percent (numbers apply to the coupé). The remaining seven percent comprises other materials and connecting elements. The outer skin, including the doors and lids, is made entirely of aluminum.

The Audi Q7 (2015)
The current Q7 is the first Audi model based on the second-generation modular longitudinal platform (MLB evo). Its curb weight is up to 325 kilograms *(716.5 lb)* lighter than that of the predecessor, due also to the considerable reduction of the body weight – the multi-material body integrates large parts made of hot-formed steel and aluminum, and that alone saves 71 kilograms *(156.5 lb)*. Also contributing to the weight savings are the body add-on parts, which account for a reduction of 24 kilograms *(52.9 lb)*.

While ultra-high-strength steel components are used for the occupant cell's safety cell, aluminum makes up a 41-percent share of the body structure. Parts such as the strut tower domes in the engine compartment and the connecting parts between the sills and longitudinal members are die-cast. The front and rear longitudinal members are made of aluminum profiles.

Aluminum sheets take up large sections of the floor, the rear wheel arches, the roof and the side wall frame. All components including doors, front fenders, engine hood and tailgate are made entirely of the lightweight metal.

Fuel consumption of the models named above:

Audi A8 (coming generation):
This car is not yet on sale. It does not yet have type approval and is therefore not subject to Directive 1999/94/EC.

Audi A8 (current model):
Combined fuel consumption in l/100 km: 11.2 – 5.7** *(21.0 – 41.3 US mpg)*;
Combined CO_2 emissions in g/km: 259 – 146** *(416.8 – 235.0 g/mi)*

Audi TT:
Combined fuel consumption in l/100 km: 8.5 – 4.6** *(27.7 – 51.1 US mpg)*;
Combined CO_2 emissions in g/km: 194 – 122** *(312.2 – 196.3 g/mi)*

Audi R8:
Combined fuel consumption in l/100 km: 12.3 – 11.4** *(19.1 – 20.6 US mpg)*;
Combined CO_2 emissions in g/km: 287 - 272 *(461.9 - 437.7 g/mi)***

Audi Q7:
Combined fuel consumption in l/100 km: 7.6 – 5.5** *(30.9 – 42.8 US mpg)*;
Combined CO_2 emissions in g/km: 199 – 144** *(320.3 – 231.7 g/mi)*

**Fuel consumption, CO_2 emission figures and efficiency classes given in ranges depend on the tires/wheels used.