Applications – Car body – Body structures

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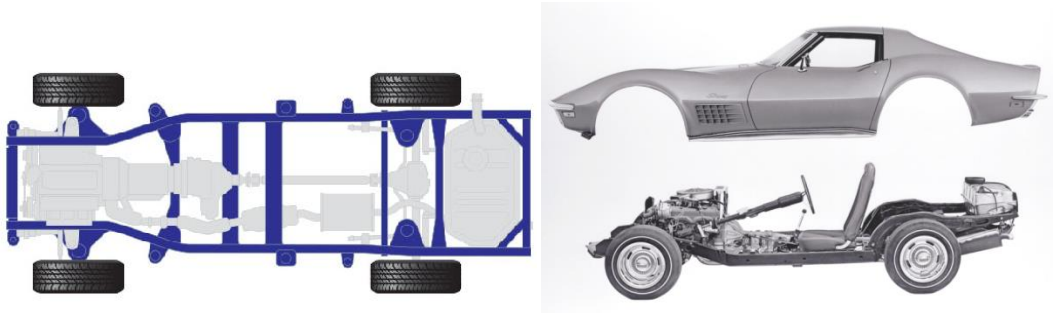
1 Body structure

The core element of any car is the body structure. The car body connects all the different components; it houses the drive train and most importantly carries and protects passengers and cargo. The body structure needs to be rigid to support weight and stress and to securely tie together all the components. Furthermore, it must resist and soften the impact of a crash to safely protect the occupants. In addition, it needs to be as light as possible to optimize fuel economy and performance. Over the years, various designs have been used and each of them has its benefits and drawbacks.

1.1 Body design concepts

The oldest structural vehicle design is the body-on-frame concept. The frame typically consists of two parallel, connected rails ("ladder frame") which the suspension and power train are attached to. The rest of the body, or the shell, sits on the frame.



The ladder frame design (left) as exemplified by the Chevrolet Corvette C3 (right)

The body-on-frame concept was used until the early 1960s by nearly all cars in the world. The original frames were made of wood (commonly ash), but steel ladder frames became common in the 1930s. Today, the frame design is only employed for light trucks and full-size SUVs. The frame looks like a ladder, two longitudinal rails connected by several lateral and cross braces. The longitude members are the main stress member. They deal with the load and the longitudinal forces caused by acceleration and braking. The lateral and cross members provide resistance to lateral forces and increase the torsional rigidity.
Frames are used on trucks because of their overall strength and ability to sustain weight. The disadvantage of the frame design is that it is usually heavy and – since it is a two-dimensional structure − the torsional body stiffness needs to be improved. Also, the frame tends to take up a lot of valuable space and forces the centre of gravity to go up. Safety is also compromised in a body-on-frame vehicle because the rails do not deform under impact; i.e. more impact energy is passed into the cabin and to the other vehicle.
Most small car models switched to the monocoque construction in the 1960s, but the trend already started in the 1930s with cars like the Opel Olympia. Today, the monocoque design is by far the dominating body concept. The Ford Crown Victoria (discontinued in 2011) was the last passenger car using the body-on-frame concept.
The monocoque design is a construction technique that utilises the external skin to support some or most of the load (in contrast to the body-on-frame concept where the frame is merely covered with "cosmetic" body panels). In this case, the integral floor pan serves as the main structural element to which all the mechanical components are attached. But there are also "semi-monocoque" variants, e.g. the Volkswagen platform concept which includes a lightweight, separate chassis made from pressed sheet panels. In this case, both the chassis as well as the body shell are used to provide the necessary structural strength.

The monocoque construction is a one-piece structure which defines the overall shape of the car and incorporates the chassis into the body. In fact, the "one-piece" chassis and body are made by welding many stamped sheet panels together. The monocoque body structure offers good crash protection as crumple zones can be built into the structure. Another advantage is space efficiency since the whole structure is actually an outer shell. Obviously, this is very attractive to mass production cars. But while the monocoque structure is highly suitable for mass production by robots, high tooling costs hinder its application for small-scale production. Also the pure monocoque structure is relatively heavy. The rigidity-to-weight ratio is fairly low as the shell is shaped to benefit space efficiency rather than strength and the pressed sheet panels are not as stiff as structures made from tubes or other closed sections and/or three-dimensional components.

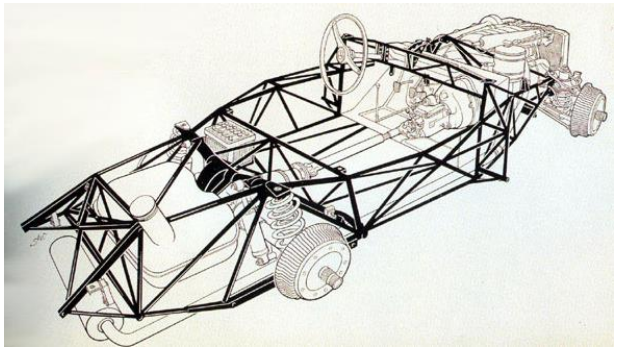
Consequently most modern car bodies are not true monocoque designs; instead today's cars use a unitary construction which is also known as unibody design. This uses a system of box sections, bulkheads and tubes to provide most of the strength of the vehicle, to which the stressed skin adds relatively little strength or stiffness.

Unibody design concept

The unibody design allows a significant weight reduction of the car body and enables a more compact, yet spacious vehicle configuration. Also safety is increased because energy-absorbing deformation zones can be engineered into the unibody. The rigidity of the car body is somewhat compromised because the basic monocoque assembly is made of sheet panels which are – at least in case of steel designs – generally spot welded, i.e. only locally connected. However, it is easily possible to increase the stiffness of the unibody by using continuous joints (e.g. adhesive bonding or laser welding) or by the addition of tubes, closed sections or other stiffening components. On the other hand, when a vehicle with a unibody design is involved in a serious crash, it may be more difficult to repair than a full frame vehicle.

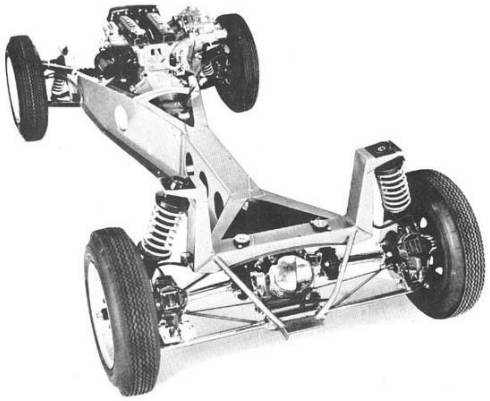
Suspension components, as well as the power train, are directly mounted to the unibody. In many cases, subframes are used as strong mounting interfaces. Additional important structural parts are the firewall (located between the passengers and the engine compartment) and, sometimes, also the wall behind the back seats. This is also the case for the body panels which serve as the skin of the car and give the vehicle its overall shape and appearance. Elaborate monocoque design is so sophisticated that windshield and rear window glass make an important contribution to the designed structural strength of the automobile too.
For niche applications, there are two additional body design concepts: the tubular space frame and the backbone chassis. As the ladder chassis is not strong enough for high performance sports cars and racing applications, motor racing engineers developed a three-dimensional design. The tubular space frame chassis employs dozens of tubes or other rod-shaped components, positioned in different directions to provide the required mechanical strength against forces from anywhere. The result is a very complex welded structure. Since the mid 60s, many high-end sports cars also adopted the tubular space frame design to

enhance the rigidity / weight ratio. However, many of them actually used space frames only for the front and rear structure and used a monocoque cabin for cost reasons.



Tubular space frame design of the Mercedes-Benz 300SLR racing car

The backbone chassis is very simple. It consists of a strong tubular backbone (usually with a rectangular cross section) which connects the front and rear axle and provides nearly all the mechanical strength. The whole drivetrain, the engine and the suspensions are connected to both ends of the backbone. The backbone chassis is strong enough for small sports cars, but not suitable for high performance sports cars. Also it does not provide any protection against side impact and off-set crash.



Backbone chassis of the Lotus Elan
(Photo: Lotus)

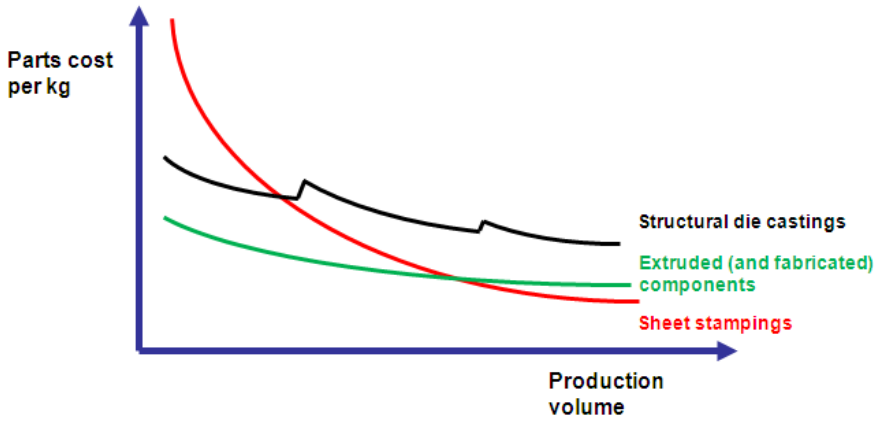
1.2 Car body design with aluminium

Steel car bodies have been traditionally fabricated from stamped sheet parts joined by resistance spot welding. Newer developments included the introduction of the hydroforming technology and the laser beam welding technique. Together with the market introduction of new high and ultra high strength steel grades, it was thus possible to improve the stiffness and crash worthiness and/or reduce the weight of the steel car bodies at no or little additional cost. Laser welded, continuous joints significantly increase the rigidity of the monocoque body structure and structural components and subframes manufactured from thin, hydroformed steel tubes enable further improvements of the body strength and stiffness.
Similar design and manufacturing principles as used for steel body structures can be applied to realize an all-aluminium car body. However, simple material substitution leads not always to cost efficient solutions. It is essential to take a holistic approach and to consider the total system consisting of the construction material, appropriate design concepts and applicable fabrication methods. Technically and economically promising aluminium car body concepts are the result of aluminium-oriented design concepts and properly adapted fabrication technologies. With its different product forms (sheets, extrusions, castings, etc.), aluminium offers a wide variety of design options. Therefore an appropriate substitution of steel by aluminium in the body structure enables not only a significant weight reduction, but influences

the cost efficiency too. The selection of the most appropriate product form − depending on the type of car and the planned production volume – also allows the optimisation of the technical performance under the given economical and ecological boundary conditions.
The main elements of a self-supporting car body structure ("unibody") are:

- load-carrying profiles
- stiffening sheets

and the required joining elements (nodes). The profile structure provides the basis for the required high bending and torsion stiffness of the car body within certain package restrictions. The basic body frame given by profiles and nodes is further stiffened by the addition of sheets which are also used to form the overall body enclosure. An additional design requirement is an excellent crash worthiness of the car body (high energy absorption capability by deformation without crack initiation and fracture).
A most important advantage of aluminium compared to steel is the additional availability of extruded, single- or multi-hole profiles with complicated cross sections and thin-walled, intricately shaped castings with excellent mechanical properties. These components cannot be only beneficially used for load-carrying and/or stiffening functions, but may also serve as joining elements. The proper use of extruded (and formed) or die cast products enables the development of new, innovative structural design solutions and, consequently, significant weight and cost savings by parts integration and the incorporation of additional functions.
Aluminium sheets show similar denting and bending stiffness as steel sheets when their thickness is increased by 40 %, i.e. the weight reduction resulting from a material substitution reaches up to 50 %. In case of the profiles, the substitution of steel by aluminium offers in particular potential for weight reduction when the profile geometry (cross section) can be varied, e.g. by changing from an open to a closed profile or by the introduction of multi-chamber profiles. Furthermore, there is a clear potential for the beneficial application of extruded aluminium profiles when the profile diameter can be increased.
The decisive factor in the selection of the most effective aluminium body design concept is the envisaged production volume. High volume production looks for minimum material (part) cost and low assembly cost, but can afford relatively high capital investments (both in tools and manufacturing equipment). In contrast, low volume production asks for minimum capital expenditures whereas component and assembly costs play a less important role.

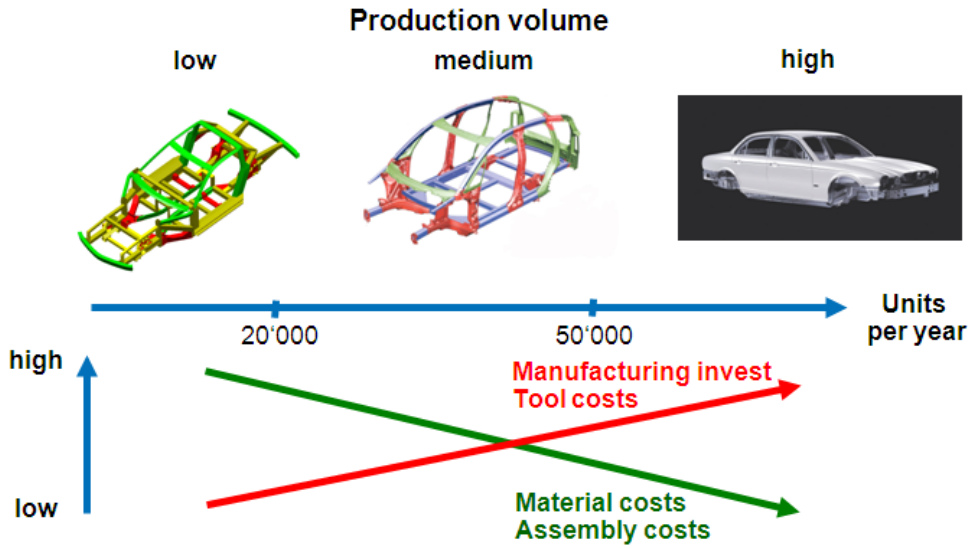


Cost of different aluminium structural body components (schematic)

The cost relations shown above for ready-to-assemble structural car body parts give only a rough indication. In practice, the actual cost of aluminium body components will vary significantly. The shapes of the components, the required geometrical tolerances and mechanical properties, etc., are most relevant parameters. The cost of extruded aluminium components differ significantly depending on the necessary additional forming and machining steps. 3D-bending and hydroforming operations are particular cost-intensive. In case of structural die castings, a most important cost factor is the (part-specific) tool lifetime. Furthermore, the assembly costs can show large differences depending on the application-specific requirements and the geometrical tolerances of the single components. But also the cost of surface preparation and corrosion protection can be significant. Thus, a detailed analysis of all the various factors influencing the overall cost will be generally necessary.

Depending on the planned production volume, the various product forms − sheets, extrusions and structural die castings − can be used in varying proportions for the car body structure. Mixed material designs, i.e. the combination with other material components (steel, magnesium, fibre reinforced composites, etc.) add further possibilities. For aluminium-intensive car body structures, however, only three basic car body design concepts are used today:

- Extrusion-intensive frame structures (straight and 2D-bent extrusions)
- Spaceframe structures including formed extrusions and large, thin-walled castings
- Sheet-intensive unibody structures.



Aluminium-intensive car body design concepts

1.3 Sheet-intensive aluminium body structures

1.3.1 Early developments

Sheet designs are primarily directed towards higher production volumes because of the high investments in stamping tools and presses. On the other hand, sheets are a relatively inexpensive product form. Sheet-intensive body design concept are established and proven for steel car bodies. They can be also realised with aluminium sheets. The Panhard Z1 model can be mentioned as a first example. Series production started in 1953 with the use of EN AW-5754 (AlMg3) alloy sheets.

In the early eighties, several aluminium concept cars were produced, in general just by the substitution of steel sheets by aluminium alloy sheets in existing car models. As an example, a Porsche 928 sports car with an all-aluminium body was exhibited 1981 at the IAA Frankfurt. The aluminium body was a joint development with Alusuisse, it was built using Anticorodal®-120 (EN AW-6016) alloy sheets (thickness 1.2 mm for the closures, 2.5 mm for the structure). The weight of the aluminium body was 161 kg, representing a weight reduction of 106 kg compared to the steel body. Soon afterwards, Audi began to study aluminium intensively again; in due course, an aluminium body based on the Audi 100 was developed.

Aluminium sheet concept car based on the Audi 100 (1985)

(Photo: Audi)

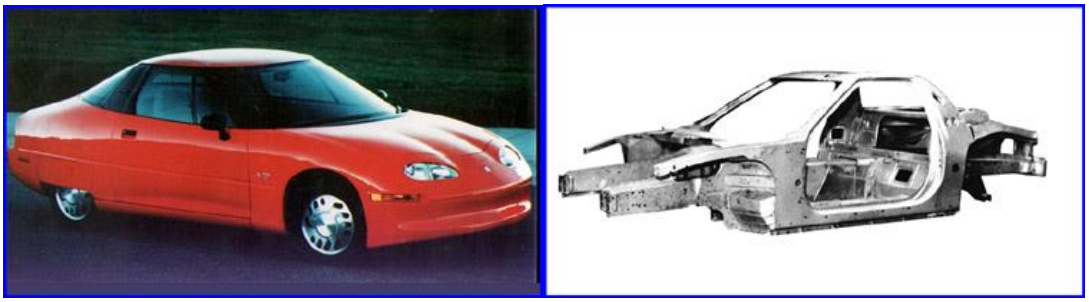
The first production car with an all-aluminium body was the Honda Acura NSX, introduced in 1989. The Honda Acura NSX, a high performance, two-seater sports car, was assembled by hand in very small numbers. It featured an all-aluminium monocoque body with a weight of 163 kg, incorporating some extruded aluminium profiles in the frame and the suspension. The application of aluminium in the body alone saved nearly 200 kg in weight over the steel equivalent while the aluminium suspension saved an additional 20 kg. The exterior had a dedicated paint process, including an aircraft type chromate coating designed for chemically protecting the aluminium bodywork. The body structure utilized high-strength aluminium alloys and special construction techniques, making it stronger than a comparable steel body, yet 40 % lighter. A combination of spot and MIG spot welding was used to join the structure together.
In addition, the NSX-T offered a removable, aluminum roof panel. This panel was designed to be lightweight, yet durable, and has its own storage compartment under the rear glass hatch.

Honda Acura NSX the first production car with an all-aluminium monocoque body

In the early 1990s, Alcan Aluminum Ltd. partnered with Ford to develop an aluminium-intensive vehicle. Ford then built a test fleet of 40 vehicles based on the design and mechanical components of its Taurus volume production midsized sedan. The P2000 features a stamped aluminium unibody similar to a conventional steel body, but it uses advanced design and fabrication technologies to achieve a stiff and safe structure. The front shock towers, for example, are aluminium castings, eliminating the need for a heavier, complex and costly three-piece stamped aluminium assembly. The P2000 also features epoxy adhesive weld bonding to improve rigidity. The resulting body-in-white has a mass of 182 kg, compared with 398 kg for a conventional steel version. Overall, the P2000 is made of about 332 kg of aluminium as well as significant amounts of magnesium and plastics, contributing to a total car weight of about 907 kg (compared to 1505kg of the steel production Taurus model).

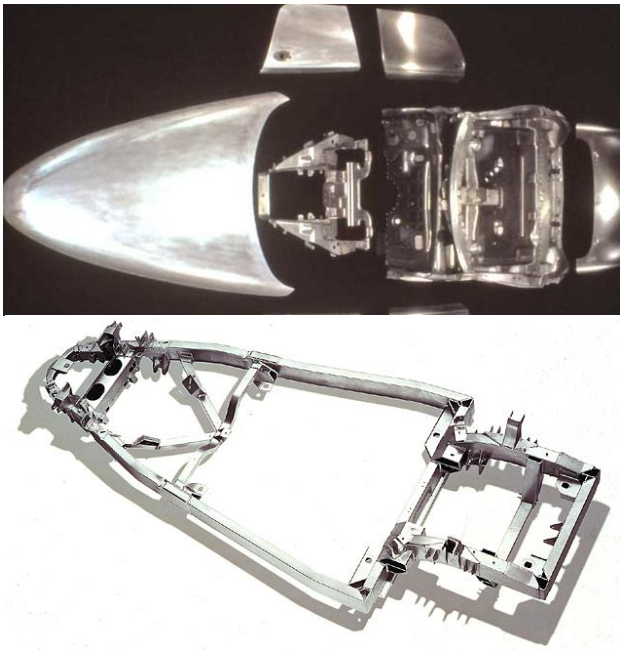
Ford P2000 prototype car (1998) produced using Alcan's Aluminium Vehicle Technology

The Ford P2000 was developed as a purpose-designed aluminium-intensive mid-sized sedan where Ford took full advantage of the primary weight saving from the aluminum body-in-white structure to reduce the weight of all the vehicle's secondary systems. The aluminium body-in-white was built using Al-3%Mg structural sheet material (EN AW-5754, 0 temper). The construction benefited from the application of Alcan's Aluminum Vehicle Technology (AVT) structural bonding system. Structural bonding (combined with resistance spot welding) significantly increases the stiffness of the body structure, particularly the torsional stiffness. This enables an increase of the weight saving compared to steel to over 50%, thereby improving the economics for using aluminium. Compared to spot welded steel, the AVT system also improves the fatigue endurance and the impact energy absorption capacity. The AVT system was first used in a production vehicle for the front longitudinal crash energy management beams for the Jaguar Sport XJ220, a limited production, high performance sports car produced in the years 1992-1994.
The body structure technology used in the P2000 program was transferred later to the platform of the prototype hybrid electric vehicle (HEV) Ford Prodigy family sedan. The Prodigy's total mass was 1083 kg, approximately 454 kg less than an average family sedan. The AVT structural bonding system (adhesive bonding plus spot welding) was also applied for the production of the frame of the General Motors EV1 electric vehicle. The GM EV1 was the first mass-produced sedan purpose-designed for electric propulsion. It was produced and leased by GM from 1996 to 1999. The car's body panels were made of plastic rather than aluminium for improved dent resistance. The body-in-white was an adhesively bonded and resistance spot welded aluminum structure and weighed only 132 kg, a savings of about 40 percent over the steel equivalent. The bonding used an aerospace-grade structural adhesive, a first for a production vehicle



General Motors EV1 with an AVT body structure

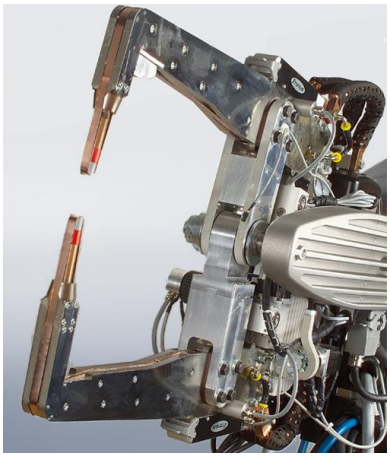
A low-risk test bed for aluminium materials was the Plymouth Prowler (built in 1997 and 1999-2002). In 2001, the car was branded as a Chrysler vehicle. The Prowler contained more than 400 kg aluminium (including body, chassis frame and suspension parts). The aluminium chassis frame consisted of 42 extrusions and 8 castings which were joined by automated MIG welding. The body panels (AlMgSi outers, AlMg inners) were joined by self-piercing rivets and epoxy adhesive. The rivets hold the panels in place while the epoxy cures in the primer paint oven. Thixo-casting was used for the production of the control arms in the front and rear suspension.



Aluminium body components and chassis of the Prowler
(Photos: Plymouth)

1.3.2 Joining technology – the key to success

The realisation of a sheet-intensive (“monocoque” or “unibody”) structure requires a very large amount of joining. As a consequence, the properties of the joints have a significant effect on the overall properties of the whole structure including global stiffness, NVH (noise, vibration, harshness) and crashworthiness. The most important difference between aluminium and steel designs is the prevailing joining technique. Compared to steel, aluminium alloys show a high electrical and thermal conductivity and − correspondingly − low electrical resistance. When the resistance spot welding technique, traditionally used with steel, is applied to aluminium, the welding current must be significantly higher. Consequently, conventional resistance spot welding of aluminium proves to be energy-intensive, unreliable and costly (need for special welding equipment, sheet surface preparation prior to welding, frequent electrode cleaning, etc.). Proper solutions for these problems have been developed, but resistance spot welding of aluminium nevertheless require special effort.
A specific problem is the low electrode lifetime. A possible solution is the frequent cleaning of the electrode surface, e.g. by regular surface machining or brushing (“electrode buffing”). Successful resistance spot welding of aluminium can be also achieved with the Fronius DeltaSpot technology. In this case, the robot welding gun is equipped with a process tape which runs between the electrodes and the sheets being joined. The continuous forwards movement of the process tape results in an uninterrupted process producing constant quality, reproducible welding points and ensuring high electrode service life.



Fronius DeltaSpot robot welding gun with a process tape that runs between the sheets and the electrodes
(Photo: Fronius)

Most important for the break-through of aluminium in car body construction was, however, the further development of mechanical joining techniques and in particular the application of clinching and self pierce riveting processes in the assembly plant. Whereas the use of clinching processes is in practice limited to non-load bearing joints, self-piercing rivets (SPRs) are also suitable for joining of structural components. The mechanical joining methods are less energy-intensive than resistance spot welding and can be highly automated.
Furthermore, the resulting SPR joints have better fatigue strength properties than spot-welded aluminium joints. Self-pierce riveting is also suitable for mixed material joints (as long as both materials are significantly ductile) and is often combined with adhesive bonding. As an example, the figure below shows the cross sections of a three layer aluminium/steel joint (centre) and a joint of two aluminium sheets with an adhesive (right).

Self-pierce riveting of aluminium
(Photos: Böllhoff)

The other important joining technology for aluminium body designs is adhesive bonding. The properties of joints can be significantly improved by use of heat-cured epoxy adhesives. Normally adhesive bonds are applied in a linear form. Such joints exhibit excellent stiffness and fatigue characteristics, but should normally be used in conjunction with spot-welding, riveting or other mechanical fastening methods in order to improve resistance to peel in large deformation (i.e. during crash). Also, surface pretreatment is necessary for long-term durability of adhesively-bonded structural joints.
MIG welding is usually applied for joining of structural aluminium components (extrusions, castings and thicker sheets (> 2 mm). This is also the case for laser welding although laser welding can be also used for thinner sheets. These joining techniques are suitable for situations where there is no access to both sides of the joint or where a continuous joint is required. In special applications, also friction stir welding can be beneficially applied.

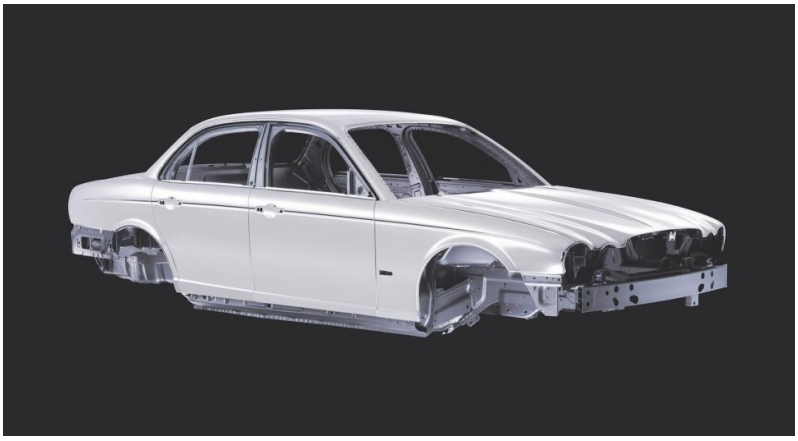
1.3.3 Jaguar's Light Weight Vehicle Technology

a) Jaguar XJ (X350)

The industrial break-through of the aluminium body in sheet monocoque design took place in 2003 with the Jaguar XJ (X350). It was the first volume-production car to use an all-aluminium monocoque chassis. Its design and fabrication concept was conceived to be suitable for high volume production (> 100.000 units per year).

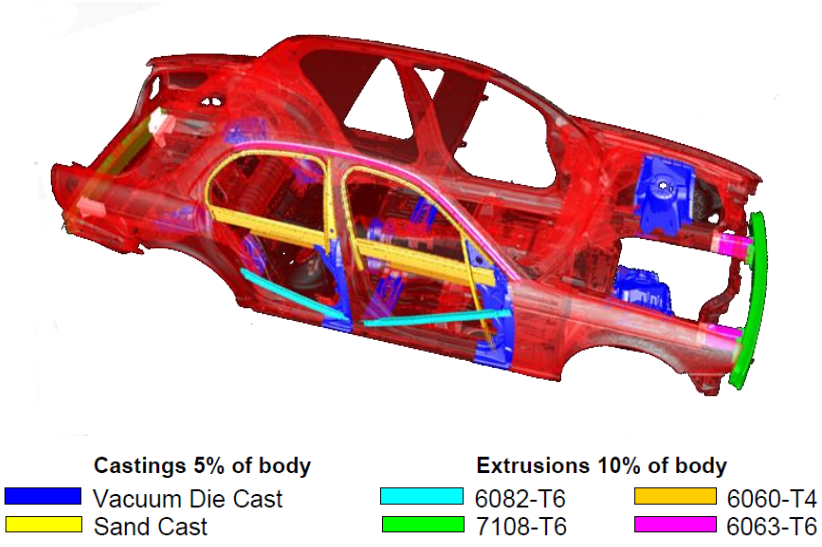
The body structure featured the first industrial use of the rivet-bonded joining technology, with self-pierce rivets and epoxy structural adhesive joining together the aluminium pressings, castings and extrusions. The extensive use of aluminium made the new XJ up to 200 kg lighter than the model it replaced, despite the fact that the new car was longer, taller and wider than its predecessor, offering improved headroom, legroom and shoulder-room for all the occupants. In addition to being 40 % lighter than that of the previous XJ, the bodyshell of the new car was 60 % stiffer, offering valuable improvements in body strength and driveability.

The application of the AVT system developed by Alcan (later Novelis) with EN AW-6111 sheets for the outer skin, EN AW-5182 inner panels and EN AW-5754 structural sheets permitted the purposeful exploitation of various cost reduction potentials existing in the entire processing chain. The weight of the painted body-in-white was 295 kg.



Aluminium body-in-white of the Jaguar XJ (X350)
(Photo : Jaguar)

The X350 body structure consisted of 273 aluminium sheet stampings, 22 extruded aluminium components and 15 aluminium castings.



Aluminium product forms in the Jaguar XJ (X350)

(Source: Jaguar)

The main joining method is adhesive bonding supported by self piercing rivets offers - as a result of the continuous joint line - a significant increase of the torsion stiffness of the body.

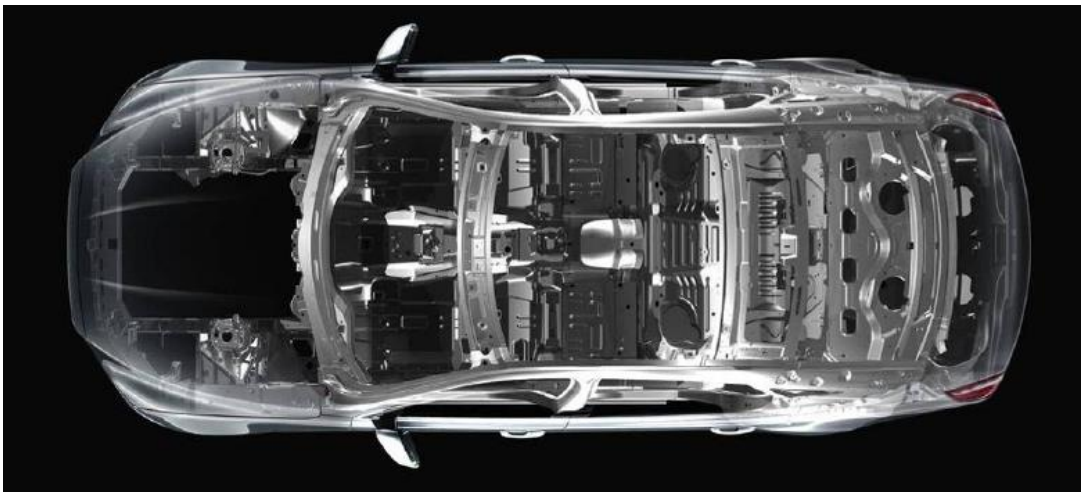
	Closures	Body less doors
Self pierce rivets	24	3171
Clinch spots	78	32
Adhesive (m)	1	100
MIG weld (m)	Nil	2
Weld studs (trim fix)	Nil	42
Weld studs (ground)	Nil	21
Blind rivets	Nil	180

Joining technologies applied in the Jaguar XJ (X350) body-in-white

b) Jaguar XJ (351)

Jaguar XJ (X351)
(Photo: Jaguar)

Production of the successor model (X351) started end of 2009 with first deliveries being made in 2010. The current XJ features a lightweight aluminium body with 50% recycled material content based on the X350 chassis and retaining a large proportion of the earlier floor pan. The weight saved - an average of 150kg compared to its competitor models - also has benefits with respect to performance and agility of the car.



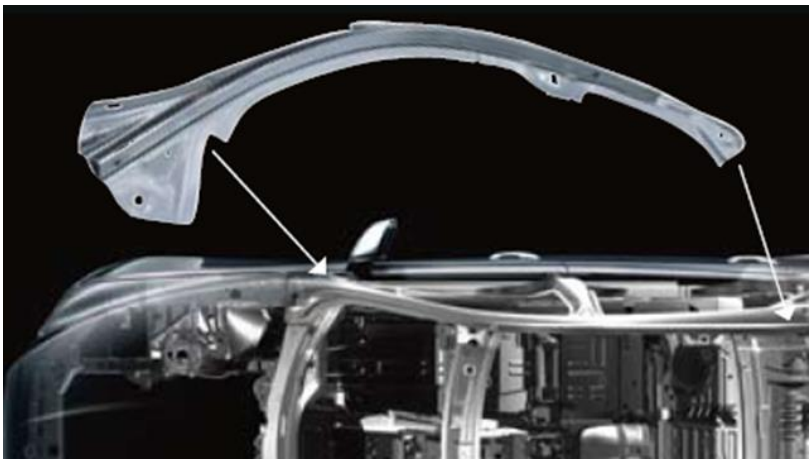
Aluminium body of the Jaguar XJ (X351)

(Source: Jaguar)

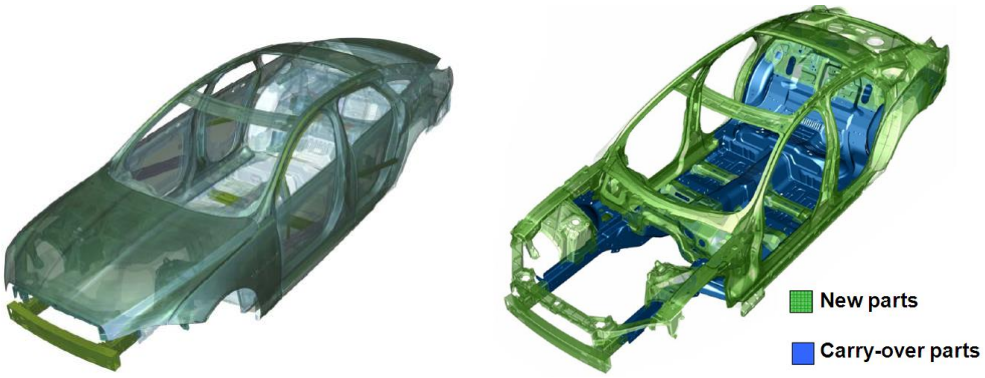
Aluminium body of the Jaguar XJ (X351)

(Source: Jaguar)

With the new XJ model, Jaguar further developed the Light Weight Vehicle technology. Compared to the previous model, the part count and the number of self-piercing rivets was reduced. However, the proportion of the different aluminium product forms was kept constant: 89 % stampings, 4 % castings, 6 % extrusions and 1 % others (by part count). An interesting new component is the high strength, pre-bent and hydroformed A post/cantrail aluminium extrusion assembly (alloy EN AW-6082-T6). On the other hand, the aluminium front end in the X350, a welded assembly of 13 components, was replaced by a single magnesium casting.

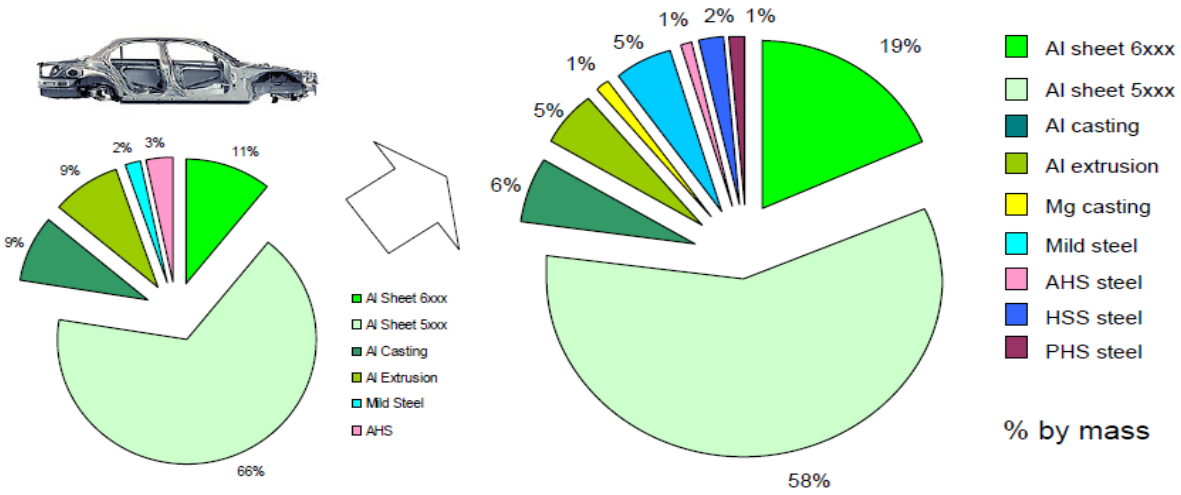


Extruded and hydroformed aluminium cant rail
(Photo : Sapa)



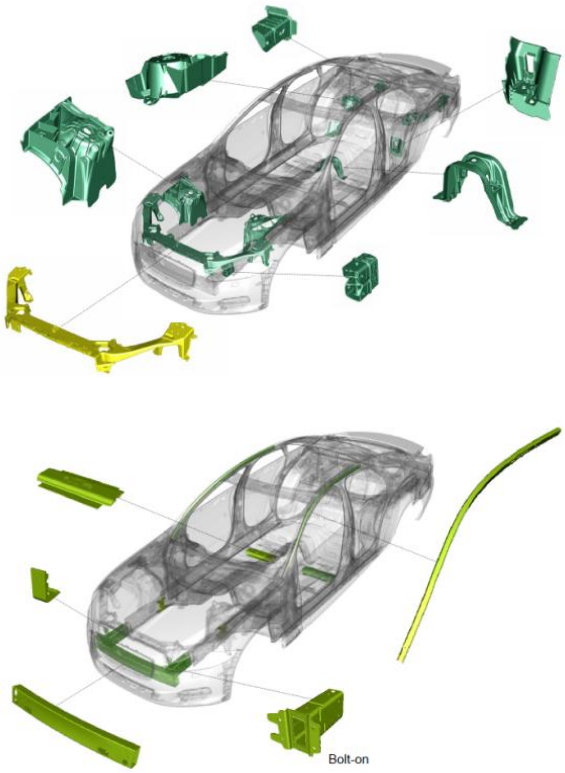
Aluminium body of the new XJ model with carry-over parts (right)
(Source: Jaguar)

The most important change from the X350 to the X351 model is the increasing use of higher strength aluminium alloys of the EN AW-6xxx series. The high-strength EN AW-6111 aluminium sheet alloy is used for the outer skin of the new car including complex parts such as the complete body side. A new door design concept with a one piece EN AW-5182 inner panel resulted in a significant weight and cost reduction. An innovative approach has been taken with the selection of Anticorodal®-300 in the T61 temper for structural parts with lower formability requirements such as the rear rail reinforcements. The supply of the material in a not fully age hardened condition increases the final strength of the component, but still offers the required formability to produce the part. Additional weight reduction was achieved by the introduction of a magnesium front end carrier and a hot formed steel side impact beam.



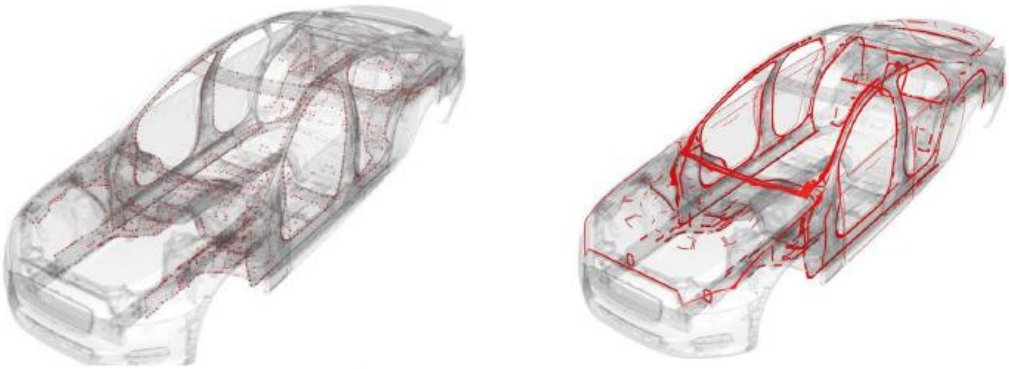
Shift of the materials applied in the Jaguar XJ: X350 → X351
(Source: Jaguar)

Aluminium castings are used in key areas for components with complex geometries used to increase the stiffness in high load areas, in particular to enable part integration (i.e. cost reduction) and to reduce multiplr sheet stack-up issues. High strength aluminium extrusions are primarily applied to minimize weight and to meet package requirements. The bolt-on crash boxes are for included for easy repair. Both aluminium extrusions and castings are joined to other parts by self-pierce riveting.



Cast (left) and extruded (right) aluminium parts in the Jaguar XJ (X351), the yellow component is a magnesium casting
(Source : Jaguar)

In the new XJ, the concept of the bonded and riveted aluminium monocoque body structure was further refined. Self-piercing rivets and adhesive bonding are the main joining technologies. Although the new XJ s larger and fulfils higher requirements, the number of self-piercing rivets could be reduced by 11 % to 2840 (compared to 5000 spot welds for an equivalent steel body). On the other hand, the length of the adhesive bonds was increased by 50 % to a total of 154 m. Furthermore, the need for MIG welding was eliminated from the assembly plant.



Main joining methods: self-piercing rivets (left) and adhesive bonding (right)
(Source : Jaguar)

c) Jaguar XK

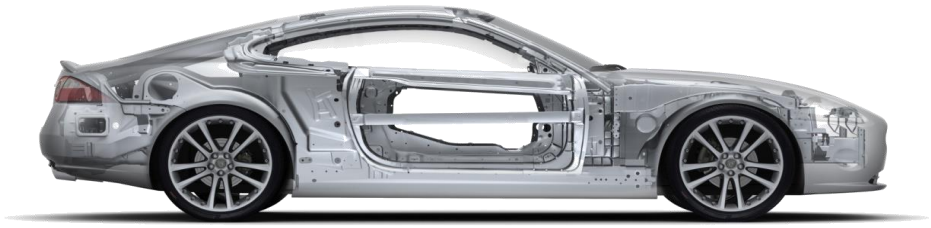
Jaguar XK (X150)

(Photo: Jaguar)

In 2006, Jaguar presented the new XK, a high-performance luxury automobile designed for long-distance driving (grand tourer). It is available both as a two-door coupe and two-door cabriolet/convertible. The second generation XK has an aluminium monocoque body shell as introduced by Jaguar with the XJ sedan. However, the XK needed a properly adapted solution since for a coupe, the package restrictions are more stringent and also a version without a roof was foreseen.

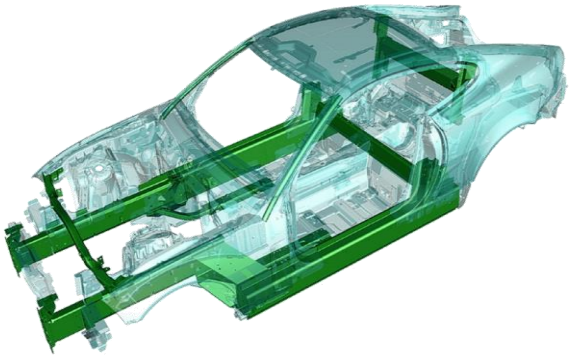
The new XK takes the Light Weight Vehicle concept a step further with extended use of lightweight aluminium castings and extrusions as well as the stamped aluminium panels. There is only a single welded joint in the new XK coupe body, a rather “cosmetic” joint on the roof. All the other joints in the new XK shell are formed using a combination of riveting and bonding. The application of the epoxy bonding and riveting techniques produces a very rigid, but also light chassis. In the coupe version, it is more than 30 % stiffer than last-generation steel model; in the convertible version, the torsional stiffness is actually increased by 50 %.

With lower weight and higher rigidity, the Light Weight Vehicle body design concept provides the basis for improved performance, safety, economy, emissions performance and driving dynamics in the new XK. In the convertible version, the body-in-white weight is just 287 kg (representing a weight reduction of 19 % compared to the previous steel XK convertible).
An advantage of the Light Weight Vehicle technology is that all the necessary stiffness is in the structure of the body shell, with very large rectangular-section side sills. The introduction of additional extrusions and castings facilitates the adaptation to the structural requirements of a coupe. In the XK, 42 aluminium extrusions are mainly used for the major load paths. As an example, the whole side sill from the A post to the back of the car is a single aluminium extrusion with a thickness of 8 to 10 mm. Thus there is no need for the traditional extra stiffening panels seen on many other convertibles. A major stiffness contribution is also due to the increased number of structural castings. Castings are specifically used for the mounting points for the engine, transmission and suspension in order to make those points significantly stiffer, further reducing transmitted noise and helping to improve suspension dynamics. Compared to the XJ sedan (X350), the share of castings was increased from 4 to 8 % and that of extrusions from 7 to 16 % (by part count)



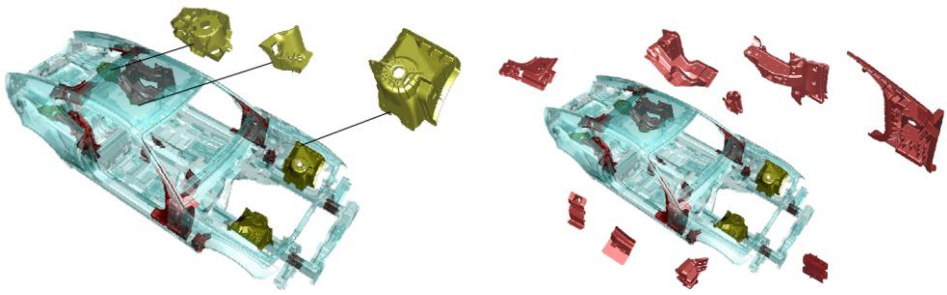
Aluminium monocoque structure of the Jaguar XK

(Source: Jaguar)



Aluminium extrusions (mostly EN AW-6014-T6) in the body of the Jaguar XK
(Source: Jaguar)

The structural castings (various alloys) are produced either by sand casting or high pressure die casting. For the sheets, the alloys EN AW-6111 and EN AW-5754 are used (as in the XJ sedan).

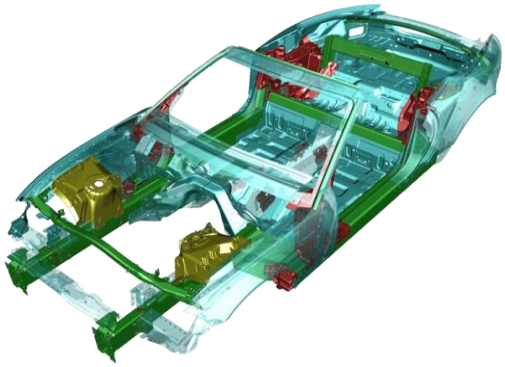


Aluminium castings in the body of the Jaguar XK: carry-over parts from the XJ (left) and new parts (right)
(Source: Jaguar)

Self-piercing rivets and adhesive bonding remain the predominant joining technologies. An important change is, however, the introduction of a 2K adhesive for heavy gauge joints (extrusions and castings). For the sheet joints, the same 1K adhesive as used for the XJ sedan could be used.

	XJ sedan (X350)	XK coupe	XK convertible
Number of parts (total)	**241**	**267**	**257**
Sheet panels	230	201	195
Extrusions	14	42	40
Castings	11	24	22
Number of joints (total)	**3287**	**2938**	**2741**
Self-piercing rivets	3185	2620	2620
MIG weld (m)	0.65	0.5	n/a
Blind rivets (EJOT)	102	283	283
Adhesive bonds (m) (total)	**116**	**99**	**99**
1K epoxy (m)	100	55	55
2K epoxy (m)	n/a	33	33
Rubber based (m)	16	11	11

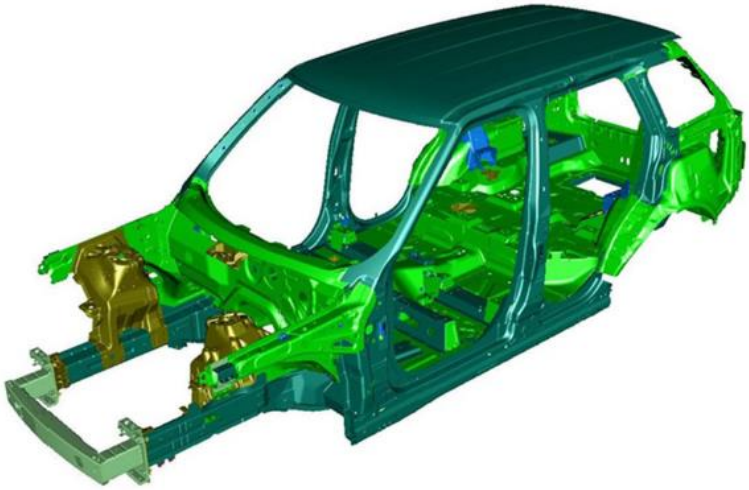
Comparison of the LWV technologies used for the Jaguar XJ and XK models (Source: Jaguar)



Aluminium product forms in the Jaguar XK (Source: Jaguar)

d) Range Rover (L405)

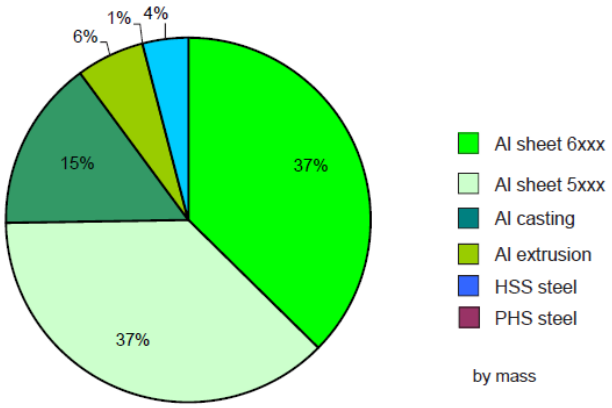
With the fourth generation Range Rover (L405) which was presented in September 2012, Jaguar's Light Weight Vehicle technology was first applied to a four-wheel sport utility vehicle. The all-aluminium monocoque body structure is 39 per cent lighter than the steel body in the outgoing model enabling total vehicle weight savings of up to 420kg. With a total body-in-white weight of 379 kg, the lightweight aluminium platform delivers significant enhancements in performance and agility, along with a transformation in fuel economy and CO_2 emissions. The optimised aluminium body structure is designed for maximum occupant protection using an incredibly strong and stable aluminium safety cell, and provides a very stiff platform for superior NVH and vehicle dynamics.



New Range Rover with an all-aluminium monocoque body structure

(Source: Land Rover)

The rivet-bonded aluminium body is more than 180 kg lighter than the steel body in the previous model. It includes aluminium stampings (88 % by part count), aluminium castings (5 %), aluminium extrusions (3 %) and a few other parts (4 %). Compared to the previous steel body, the part count could be reduced by 29 % to a total of 263 parts. The actual material breakdown per weight is shown below:



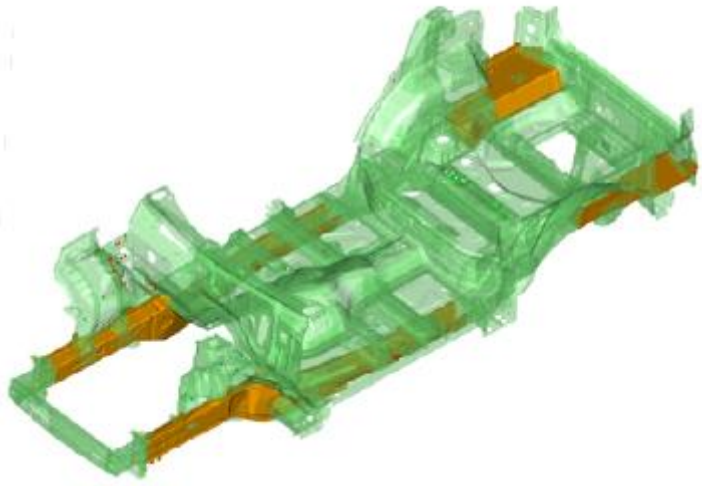
Material breakdown of the Range Rover body
(Source: Land Rover)

As in the Jaguar XJ, aluminium castings are primarily used for parts with complex geometries and to increase local stiffness in high load bearing areas. Aluminium extrusions are used in

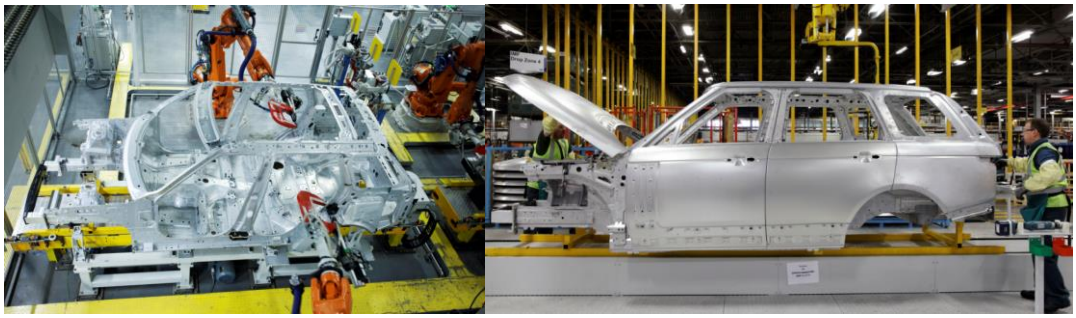
particular for the bolt-on front crash management system and the roof bow. The front end support is a magnesium casting; the upper tailgate is a SMC component.
But the Light Weight Vehicle technology has also made important advancements, in particular with respect to the applied aluminium sheets (exclusively supplied by Novelis). As an example, the entire vehicle body side is pressed as a single aluminium panel, thus reducing the amount of joints, eliminating complex assemblies and improving structural integrity. With approx. 350 x 140 cm, this is clearly one of the largest aluminium outer body stampings.

One piece bodyside, made from Anticorodal®-170 (EN AW-6014)
(Photo: Land Rover)

Other exterior body panels (e.g. the roof) are made from the newly developed high strength alloy Anticorodal®-600 PX (fits into EN AW-6181A and 6451). This alloy offers the robustness and quality of finish expected of a Range Rover, but has still a high formability. An automotive first is the use of Anticorodal®-300 T61 (EN AW-6014) in a number of crash-sensitive areas in the vehicle, including the longitudinal beam. This high-strength material has been developed for applications in the crash structure to provide an optimised crash pulse and minimum intrusion into the safety cell. It allows to down gauge the sheets by 20 % compared to the earlier alloy EN AW-5754 saving both weight and piece cost.



Applications of the alloy Anticorodal®-300 T61 in the Range Rover
(Source: Land Rover)



Assembly of the all-aluminium Range Rover
(Photos: Land Rover)

1.4 Aluminium spaceframe structure

The aluminium spaceframe design was first introduced in 1994 with the four-door, luxury sedan Audi A8. The space frame body structure was developed by Audi in co-operation with Alcoa. It is a technology perfectly adapted to aluminium as it exploits all the advantages offered by the different aluminium product forms: Sheets, extrusions and castings. Known as the Audi Space Frame® (ASF®) concept, the spaceframe construction is primarily suited for medium production volumes.

In the spaceframe concept, the roles of the various building elements of a self-supporting car body structure are clearly separated:

- Load-carrying profiles
- Stiffening sheets
- Cast joining elements (nodes).

In principle, the spaceframe creates a high-strength, stiff aluminium framework into which the larger sheet components are integrated and perform a load-bearing function. From a production-engineering standpoint, the spaceframe concept is highly flexible. Modifications can be made easily and cheaply when future model versions are introduced.

The importance of this development can't be overestimated. Cost-efficient lightweight construction with aluminium meant reinventing the self-supporting body with a new material and tailored design geometry!

1.4.1 The Audi Space Frame technology

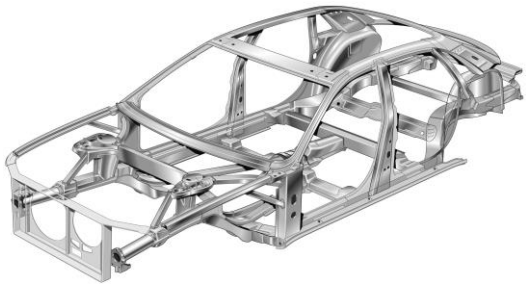
The Audi Space Frame consists of a skeleton structure largely made up of aluminium extrusions with closed cross section. The aluminium proiles can be either straight or curved (2D or 3D bent). If necessary, also multi-hole extrusions with specific cross section designs are applied. At the highly stressed corners and other joints, the frame is generally connected by complex, thin-walled aluminium nodes produced by vacuum high pressure die casting. Depending on the application, also larger, multi-functional castings are used.

Both the extrusion process and the pressure die casting technology are fabrication methods optimally suited for aluminium. They allow the production of components which can be properly adapted with respect to shape and wall thickness to meet the locally varying loading conditions. The space frame body concept exploits the possibility of high part integration (i.e. the potential reduction of manufacturing and tooling costs) and permits a weight reduction of more than 40%. Although the production of high quality structural pressure die castings and formed and machined extruded sections is relatively expensive, considerable total cost savings can be achieved for small and medium production volumes compared to pure sheet metal body design concepts. But the spaceframe construction also exhibits a substantial fraction of shaped sheet metal parts. In particular the sheet components mounted between the frame elements are most important prerequisites for the overall rigidity of the body structure.

a) Audi A8 (D2)

The Audi A8 (D2) was produced from 1994 until 2002. Its aluminium body had a weight of 249 kg (BIW plus closures), about 200 kg less than a comparable steel body. It consisted of 334 parts (47 extrusions (14 %), 50 castings (15 %) and 237 sheet stampings (71 %)). In comparison to a steel structure, the number of individual body elements has been drastically reduced (by about 25 %), saving tools, workspace and cost.

The first generation of the AUDI Space Frame included a high fraction of 2D and 3D bent extrusions (alloy EN AW-6060). For the outer body panels, the alloy Anticorodal®-120 (EN AW-6016) was used, for the inner panels EN AW-6009 and for structural panels EN AW-5182. The applied casting alloy was A356.

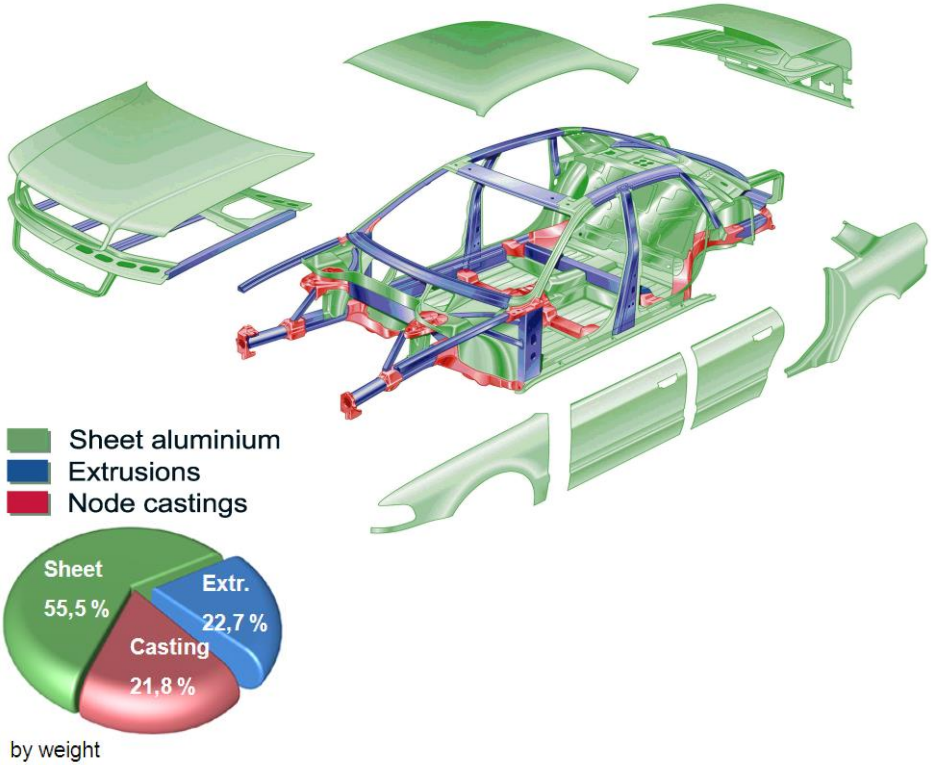


Audi Space-frame ASF®
1st Generation: Audi A8 (D2)

Aluminium spaceframe structure – Audi A8 (D2)

(Photo: Audi)

The production of the aluminium body of the first A8 (D2) model was characterized by a low degree of automation. Assembly was performed roughly 75 % by hand. The connections to the cast nodes, realized by MIG welding, were used for tolerance compensation. Another special feature of the production of the D2 body was the heat treatment of the entire assembled body at 210 °C for 30 min in the assembly plant (i.e. ahead of the paint process). The idea behind this step was to secure the necessary body strength by an “ideal” age hardening of the applied AlMgSi alloys to the T6 temper. But experience showed that a separate heat treatment of the aluminium body is not necessary; leading to the elimination of this operation already for the next Audi model with an aluminium spaceframe (A2). The required strength level can be achieved by the lacquer bake hardening step (about 20 min at 180 °C) which anyway follows the cataphoretic dip process in the paint shop.



Exploded view of Audi A8 (D2) space frame and closures

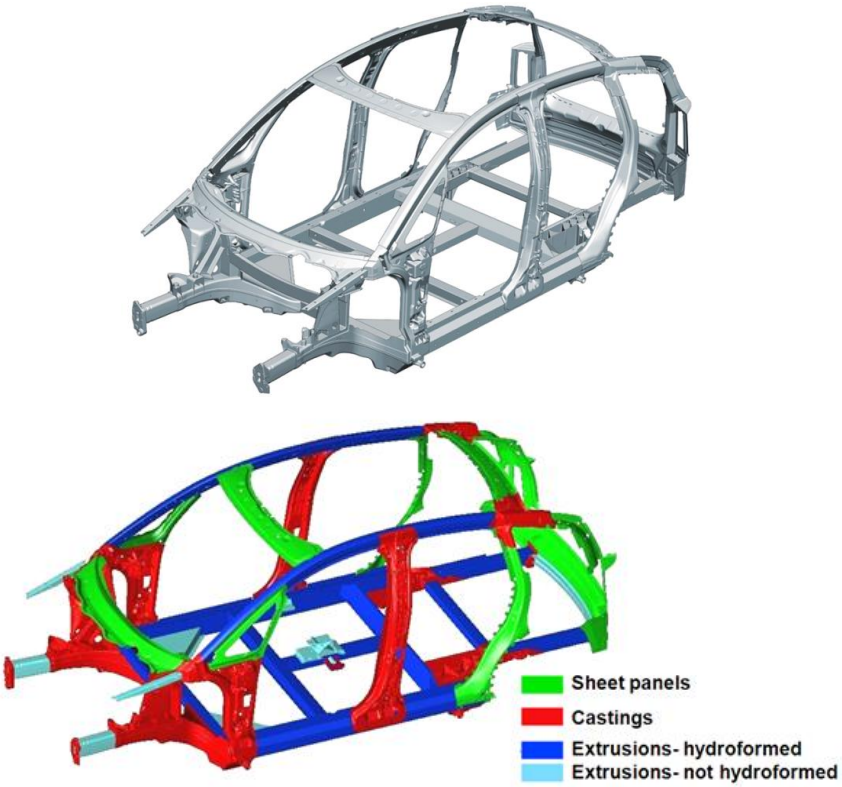
(Source: Audi)

b) Audi A2

Audi A2 – the second generation of ASF technology

(Source: Alusuisse)

Production of the Audi A2, the first mini car to be produced with an all-aluminium body in high volumes, began in 1999. Audi's development partner for the A2 body was Algroup Alusuisse (later Alcan). The weight of the A2 aluminium body was just 153 kg, 43 % less than a comparable conventional steel body. The total weight of the A2 1.2 TDI version with lightweight forged aluminium wheels and special tyres which was just 825 kg; it was the world's first five-door "three-litre" car (i.e. average fuel consumption 2.99 l/100 km).

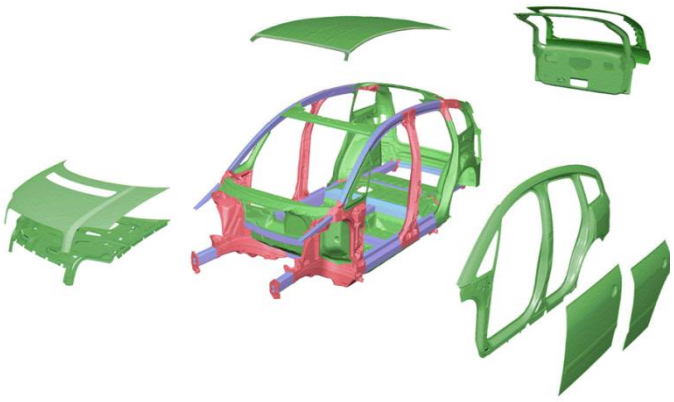


Aluminium spaceframe of the Audi A2
(Source: Audi)

The second-generation Audi Space Frame vehicle included 60 % sheet panels, 22 % castings and 18 % extruded sections (by weight). Designed for higher production volumes than the A8, it used important refinements and new developments in the areas of tools, casting and joining processes. The number of individual parts was significantly reduced compared to the A8 (from 334 parts to 225 parts):

- Stampings: 183 (81 %)
- Extrusions: 22 (10 %)
- Castings: 20 (9 %).

This has been achieved by combining various components into larger items, in most cases sections or multifunctional castings.



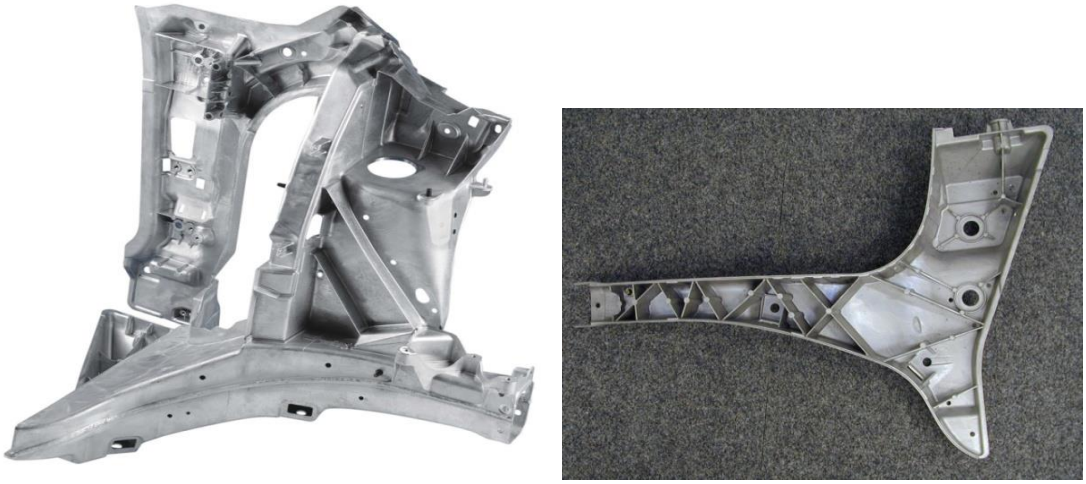
Exploded view of the Audi A2
(Source: Audi)

For example, the A2 has a single-piece side wall frame and the B-pillar comprised a single large casting whereas the B-pillar of the luxury sedan A8 was assembled from eight

components. At the same time, the weight could be reduced from 4.18 kg to 2.3 kg (although the B pillar of the A2 is slightly longer).

Cast one-piece B pillar of the Audi A2
(Photo: Alusuisse)

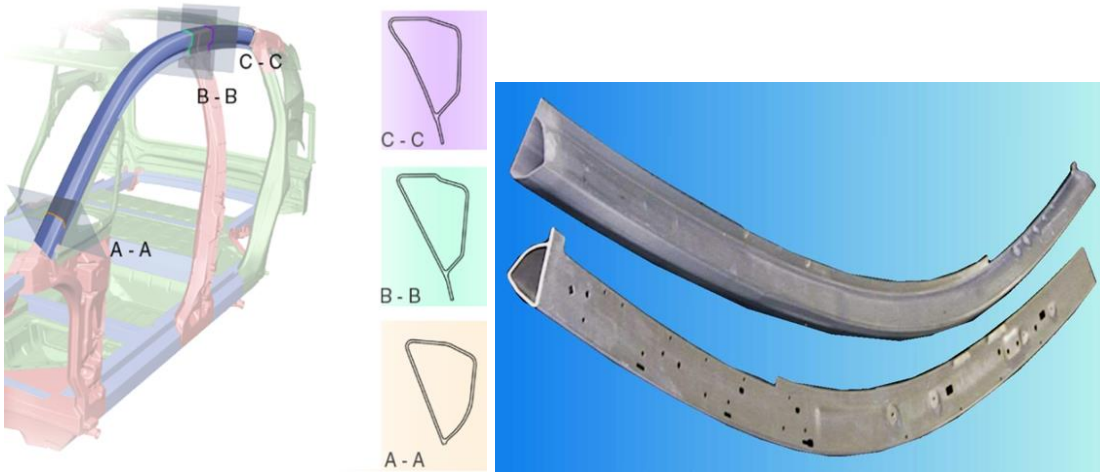
The application of a closely controlled vacuum high pressure die casting process (High-Q-Cast®) ensured that the cast components could be properly welded to the sheets and extrusions using both by laser and MIG welding. The applied casting alloy was Aural®-2 (AlSi10MgMnFe), the thermal treatment conditions were optimized to achieve high strength and good ductility while minimizing geometrical distortion of the cast part during quenching.



Assembled structural element consisting of three thin-walled aluminium castings

(Photo: Alusuisse)

The result were crashworthy thin-walled castings of complex shapes which were welded together using a MIG augmented laser welding technology.
Most of the extruded body components were hydroformed ensuring close geometrical tolerances of the straight and bent profiles. But the hydroforming process not only offers the possibility for controlled forming with narrow geometrical tolerances. In addition, piercing, stamping, length cutting and flange cutting operations could be integrated in the hydroforming process as shown below for the lateral roof frame. The alloy EN AW-6014 was used for all extrusions.

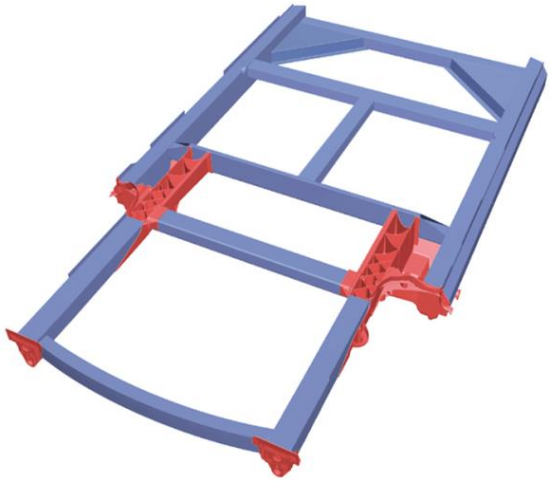


Hydroformed lateral roof frame of the Audi A2
(Source: Alusuisse)

The alloy Anticorodal®-120 (EN AW-6016) in the pre-aged state PX was used for the outer body panels; for the inner and structural panels, the alloy Ecodal®-608 (EN AW-6181A) was applied.
Three joining processes, including state-of-the-art laser welding, sufficed for the assembly of the spaceframe structure:

- Self-pierce riveting 1800 rivets
- MIG welding 20 m
- Laser welding 30 m.

The underbody frame was made up of straight extruded sections that were joined directly together by means of MIG welding, eliminating several of the different cast nodes required in the A8.



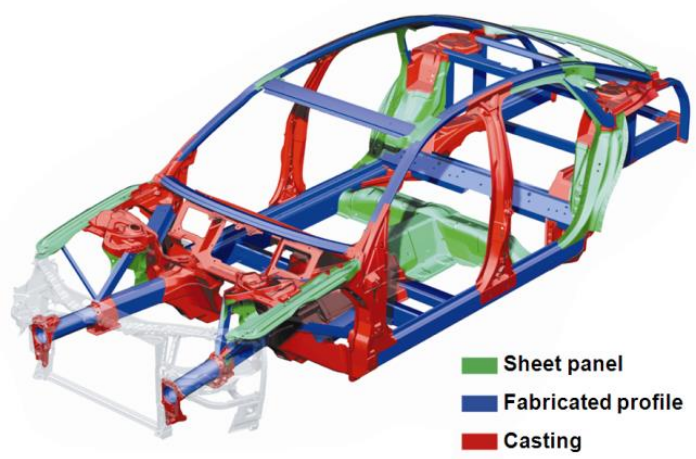
Floor structure of the A2
(Source: Audi)

The degree of automation reached roughly 85 %, a value comparable with conventional pressed-steel body construction. These measures succeed in limiting the dimensional tolerances of the structural elements to only ± 0.15 mm on the A2 - a benchmark value within the Volkswagen Group.

The A2 was considered to be "ahead of its time" in design terms—but the avant-garde styling did not win favours with customers. Audi was disappointed with the level of sales; the final production is estimated to be 175000 units.

c) Audi A8 (D3)

Production of the second generation of the Audi A8 (D3) started in 2002. Based on the experience with the A2, the number of body parts has been reduced and the degree of automation in the production process was significantly increased compared with the previous A8. Specific design features include multifunctional large castings, long continuous profiles and a high proportion of straight extruded sections. Curved profiles are only used where it is necessary for the outer paneling of the A8 (for instance the side of the roof frame). In contrast to its predecessor, the new A8 has a continuous space frame which includes the rear structure. This leads to a reduction of the share of the sheet panels in the space frame from 55 to 37 % (by weight) whereas the share of castings increased to 34 % and that of profiles to 29 %.
The weight of the all-aluminium body of the D3 (body-in-white plus closures) is 277 kg. The sheet alloys were taken over from the A2 (Anticorodal®-120 PX (EN AW-6016) for the outer body panels, Ecodal®-608 (EN AW-6181A) for the inner and structural panels). AlMgSi alloys similar to EN AW- 6060 were used for the extruded components. If necessary, the extruded sections were bent on CNC stretching and rolling machines. Where close tolerances (± 0.3 mm) were required, the semi-finished parts were calibrated and shaped by hydroforming (11 different components). In addition, also mechanical calibration was adopted for the first time for the A8 as a lower-cost technique.

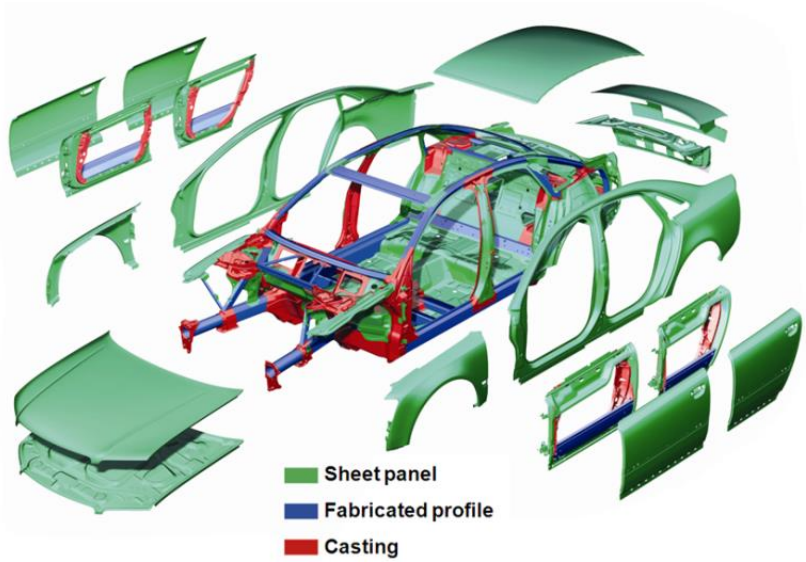


Audi Space Frame of the Audi A8 (D3)
(Source: Audi)

Whereas for the sheet and extruded components, the production techniques proven from the A2 were used, green sand casting was used for the first time in addition to the familiar vacuum high pressure die-casting methods. The applied casting alloys were GD-AlSi10Mg, GD-AlMg3Mn and for the sand castings AlSi7Mg. The multifunctional large castings used in the D3 represent systematically refined versions of those used in the A2. Special attention was placed on functional integration and on the reduction of the number of parts.

Audi A8	D2 (1994)	D3 (2002)
Sheet panels	237	168
Extrusions	47	53
Castings	50	29
total	**334**	**250**

Comparison of the parts count



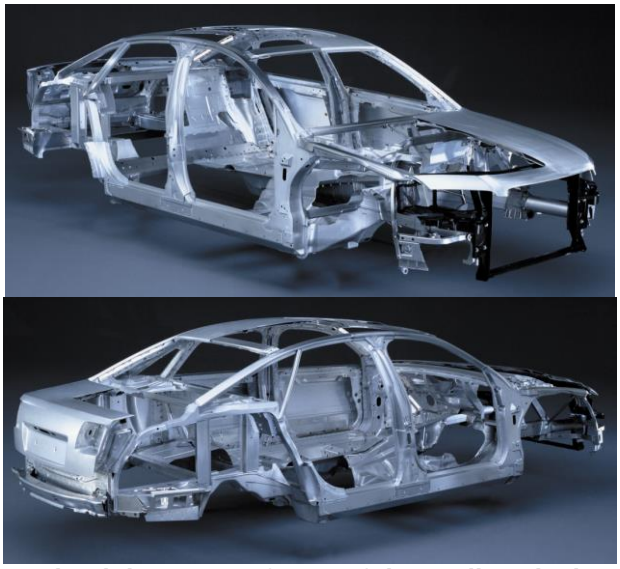
Explosion view of the body structure of the Audi A8 (D3)
(Source: Audi)

For the series production of the D3 model, the joining techniques applied in the previous A8 (MIG welding and self pierce riveting) as well as the laser welding technique introduced for the A2 have been further optimized. In addition, laser hybrid welding was used for the first time, exploiting the advantages of both MIG and laser welding while simultaneously enabling higher processing speeds. MIG welding was used predominantly for joining individual extruded sections or die-cast components, and for joining extruded sections to castings. Laser welding was mainly used for joining large-area panels with the body structure. As access for welding is only needed from one side, panels can also be joined to hollow extruded sections or castings. Nd:YAG solid-state lasers with a power output of 4 kW were used. Due to the specific hot-tearing tendency of the AlMgSi alloy group, all welds in the D3 Audi Space Frame were made with the addition of filler metal.

	D2 (1994)	D3 (2002)
Self piercing rivets	1100	2400
Resistance spot welds	500	-
Clinched joints	178	-
MIG welds (m)	70	64
Laser welds (m)	-	20
Hybrid welds (m)	-	5

Joining techniques for the Audi A8 aluminium spaceframe

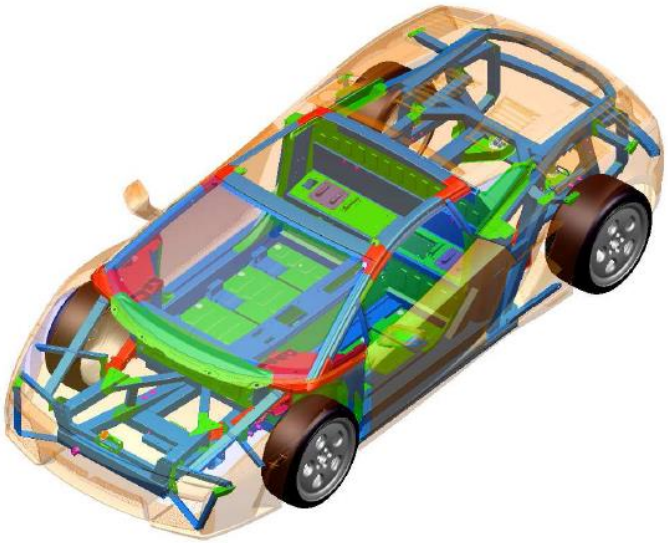
The self-piercing rivet technology was used on an extensive scale, both in the body structure and for the production of the closures. Sheet panels, extruded sections and die-castings of various alloys needed to be joined together to produce overall material thicknesses ranging from 2.0 to 6.0 mm. Only three different rivet geometries of the same hardness are used for around 100 different combinations of materials and material thicknesses with various finishes. There are also 17 m of structural adhesive bonding.
Inner and outer panels on doors and lids were joined by roller-type hemming and bonding with the aid of robotically held tools. The advantages of this method are the short familiarization time, high flexibility and a better quality and appearance of the fold. Pre-hardening of the adhesive was achieved by means of integral inductive heating.



Aluminium space frame of the Audi A8 (D3)
(Photo: Audi)

d) Lamborghini Gallardo and Gallardo Spyder

Lamborghini, a subsidiary of Audi, presented the first generation Gallardo in 2003. The Gallardo Spyder with a fully retractable soft top followed in 2006. The Gallardo used an aluminium space frame, based on aluminium-extruded parts welded to aluminium cast joint elements. On this structural frame, the exterior aluminium body parts were mounted by differentiated systems (rivets or screws or welding) depending on the function of the part. Other external hang-on parts (such as the front and rear aprons, side sill panels and fenders) were made of thermoplastic material and connected by bolts.

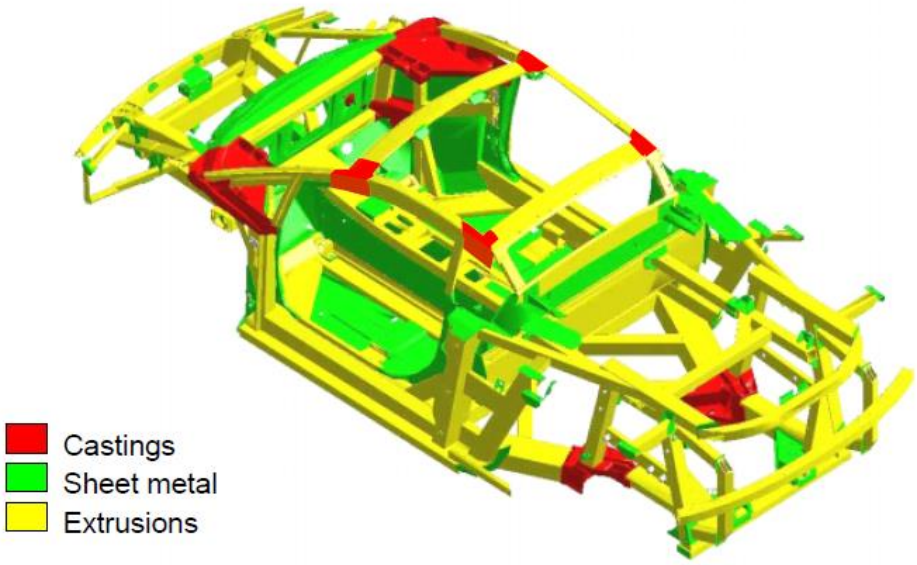


Lamborghini Gallardo

(Source: Audi)

The entire aluminium space frame of the Gallardo was built by ThyssenKrupp Drauz at Neckarsulm. It only weighs 199 kg or 239 kg for the complete body-in-white (incl. doors and lids). A most challenging task was the realization of a niche production for an aluminium space frame. Manual MIG welding was used as the main joining technology. In total, there are 115 m of MIG welds (thereof about 5 m visible welds on outer panels). In order to reduce the required amount of weld finishing, also adhesive bonding was applied on the outer body shell.

In addition, about 1300 self-piercing rivets, 100 blind rivets and 200 self-cutting screws ("Flow Drill Screw" system) are used. However, there was neither structural adhesive bonding nor laser welding.

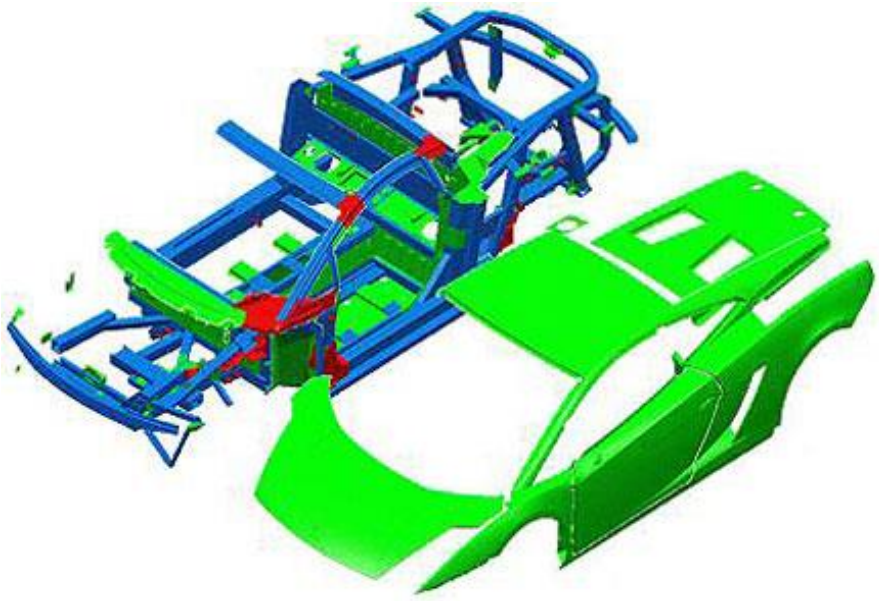


Aluminium product forms in the Gallardo space frame

(Source: Audi)

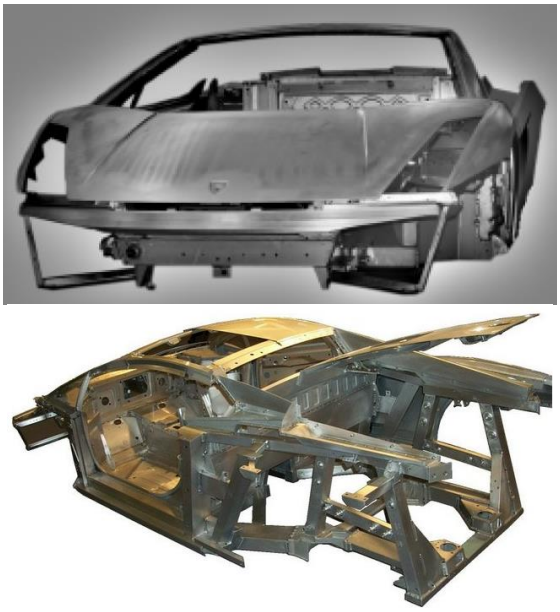
The Gallardo aluminium space frame consists of 53 % extrusions (yellow), 37 % sheet panels (green) and 10 % castings (red). The applied alloys are:

- EN AW-6060 for the extrusions
- AlSi7 for the green sand castings
- En AW-6016 for the outer and EN AW-6181 for the inner panels.



Aluminium body-in-white of the Lamborghini Gallardo

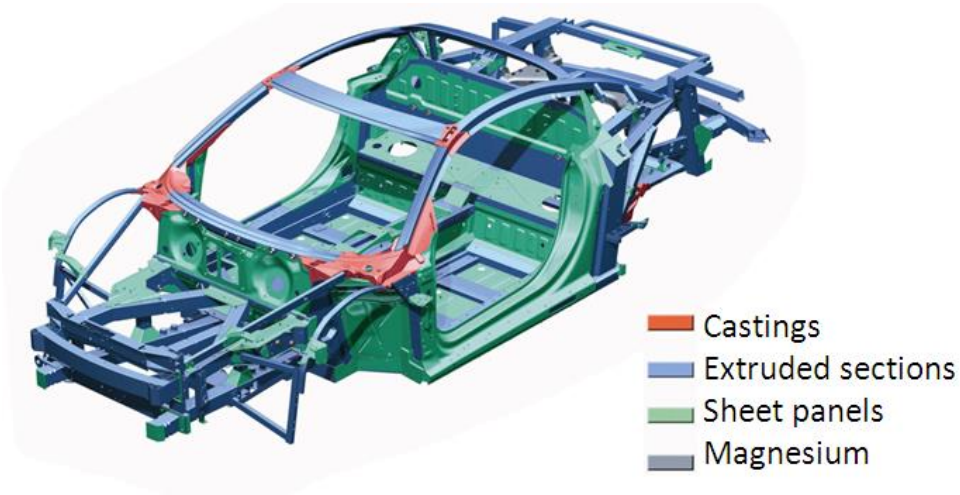
(Source: Lamborghini)



Aluminium spaceframe of the Gallardo (front and rear view)
(Photo: Lamborghini)

e) Audi R8 and Audi R8 Spyder

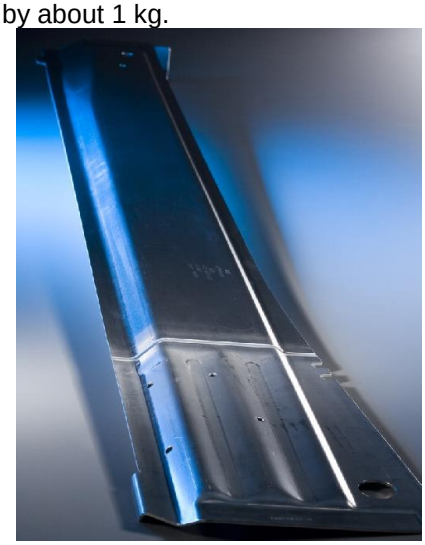
The Audi R8 is a mid-engine, two-seater sports car which was introduced in 2007. The car was built in Neckarsulm by quattro GmbH, a subsidiary of Audi. The ASF body of the R8 did set new standards in the high-performance sports car segment in terms of lightweight quality – the relationship between size, weight and rigidity. The design of the R8 spaceframe clearly shows similarities to that of the Lamborghini Gallardo. But the Audi R8's wheelbase is stretched by 90 mm to provide extra luggage space and the chassis is also considerably taller to give more headroom.



The Audi Space Frame of the R8 sports car
(Source: Audi)

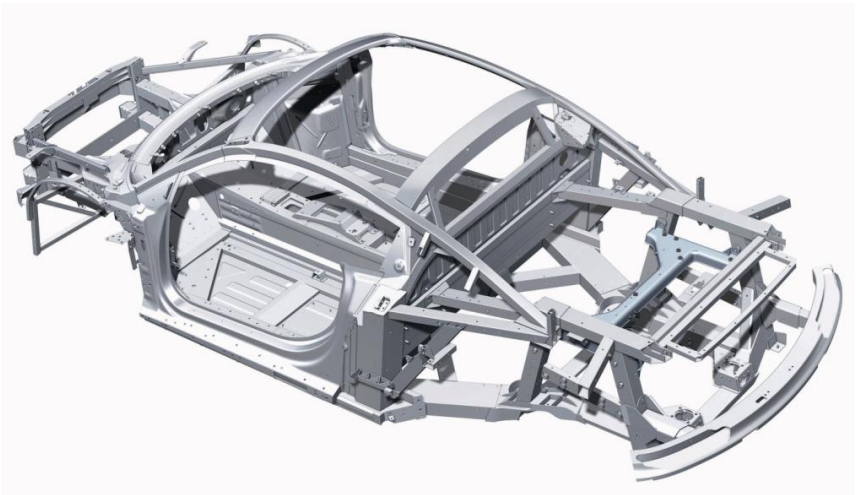
Weighing only 210 kg, the superstructure of the R8 coupe made extensive use of extruded aluminium sections which account for 70 % of the total. Vacuum-cast nodes account for 8 %, and aluminium panels make up the remaining 22 %. A magnesium engine frame provided added rigidity in the upper section of the rear end.
An interesting part in the Audi R8 was the cover sheet for the tunnel, a tailor-welded blank produced by friction stir welding. Two Ecodal®-608 (EN AW-6181A) sheets of 1.7 and 2.4 mm

are welded together. The application of the tailor-welded blank reduces the material usage by 20 % and the vehicle weight by about 1 kg.



Tailor-welded aluminium cover panel for the tunnel
(Photo: Riftec)

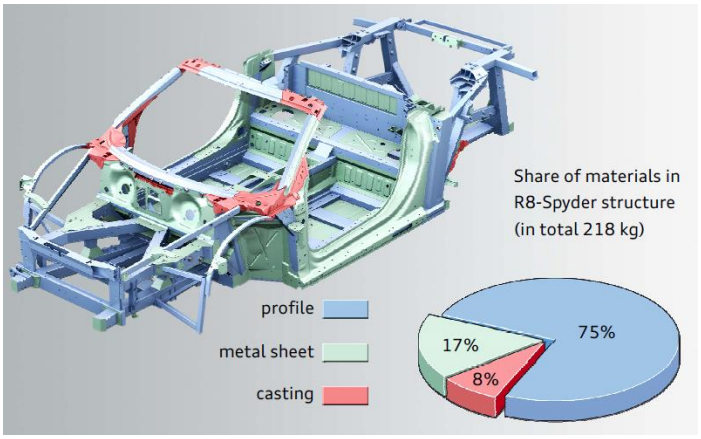
Plastic is used for the R8's front fenders and the sill liners. The hood is made of composite materials; the side blades are optionally available in carbon fibre-reinforced plastic (CFRP).



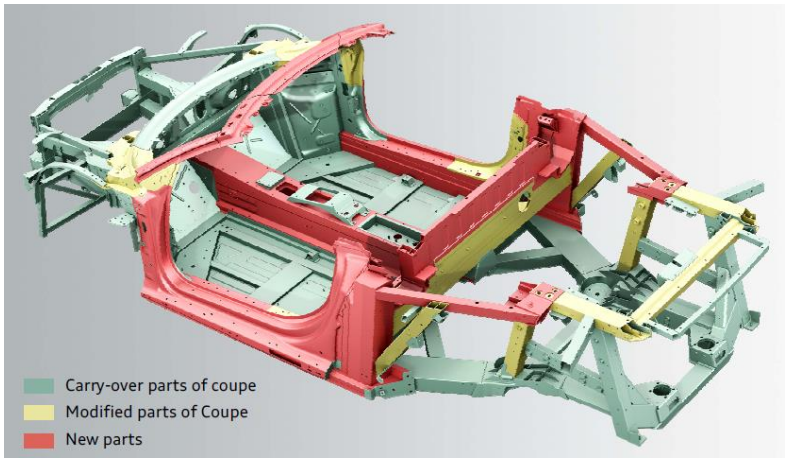
Spaceframe body structure of the Audi R8
(Source: Audi)

The coupe version was followed in 2009 by the Audi R8 Spyder. In the R8 Spyder (with a body weight of 218 kg), extruded profiles dominated the mix even more clearly than in the Coupé, accounting for 75 % by weight. There were in total 155 extrusions with 96 different

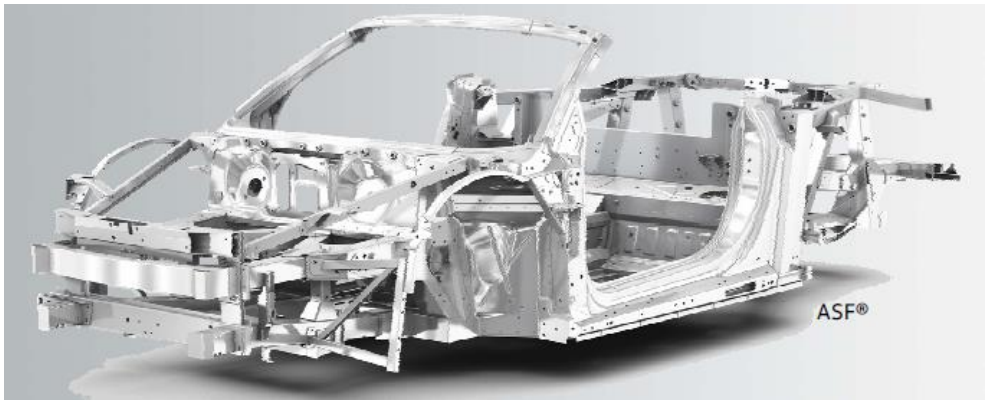
cross sections. About 20 % of the extrusions, i.e. all extruded components in the crash load path, were made from high strength aluminium alloys. An important design requirement was the maximum utilization of carry-over parts of the R8. The same cast components were used as in the R8 coupe, although the cast parts connecting the A post to the front end were slightly modified. Also the sheet panels were essentially carry-over parts.



Aluminium product forms in the Audi R8 Spyder (Source: Audi)



Audi R8 Spyder: Necessary modifications of the R8 spaceframe (Source: Audi)



Aluminium space from of the Audi R8 Spyder (Photo: Audi)

The weight of the spaceframe of the R8 Spyder is 218 kg, the weight of the body-in-white including the aluminium doors, hood and front fenders 261 kg. There is also a thin aluminium cover over the luggage compartment. The structure of the open high-performance sports car

integrates the rear side walls and the cover of the storage compartment for the top as load-bearing CFRP components. The rear bonnet is a SMC component.

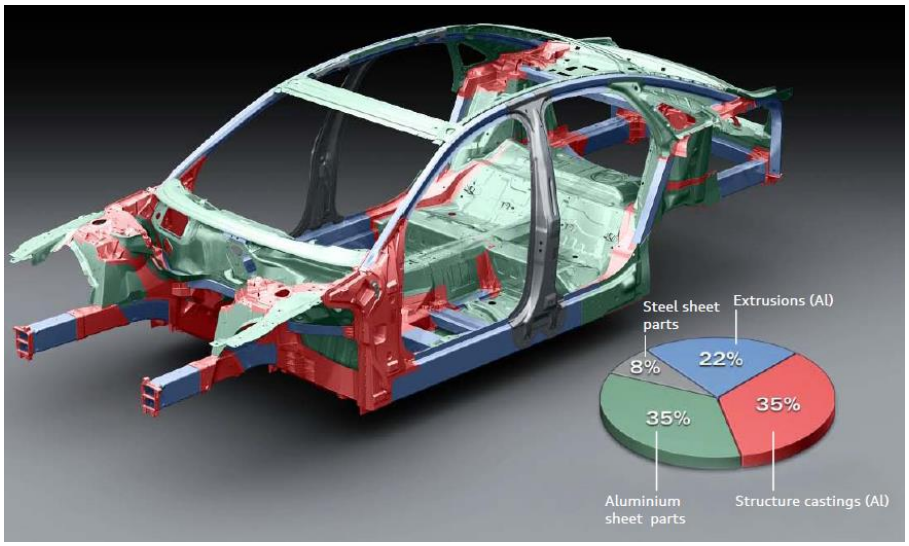
Carbon fire reinforced plastic components in the body shell of the R8 Spyder (Source: Audi)

f) Audi A8 (D4)

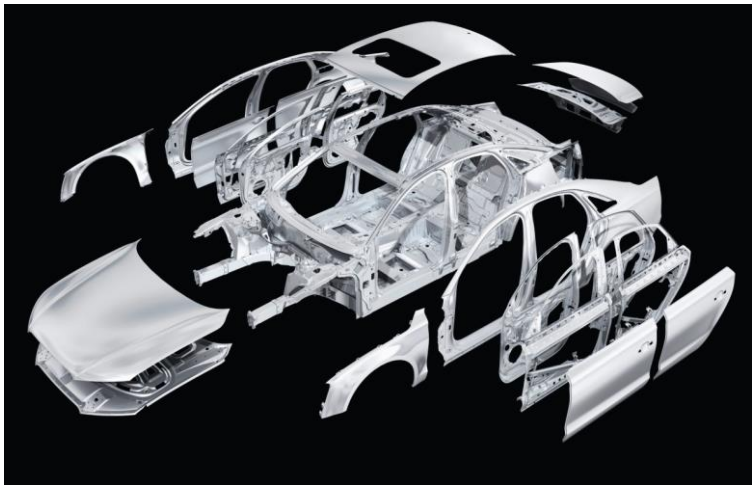
The third generation of the Audi A8 (D4) was presented in late 2009. The D4 model continues Audi's leadership in aluminium car body design and manufacturing. A key achievement was the increase of the static torsional rigidity by 25 % coupled with a weight reduction compared to the D3 model leading to an improved fuel consumption, better handling and benchmark-levels of passive safety. The body of the sedan with the standard wheelbase weighs just 231 kg; the long wheelbase model 10 kg more.

In the development of the D4, the overall target was consistent lightweight design for the complete body-in-white and structural optimization for highest functionality. Some specific examples:

- A new door design concept allowed a reduction of the vehicle weight by 11 kg.
- The spare wheel well was made from reinforced plastic with 60 % glass fibres.
- A single-piece plastic/aluminium hybrid solution was chosen for the front end.
- Partially form hardened steel components were integrated into the aluminium body (B pillar).



Audi A8 (D4): Materials in the Audi Space Frame (Source: Audi)



Explosion view of the Audi A8 (D4)
(Source: Audi)

The further development of the Audi Space Frame technology has led to a continuous reduction of the number of parts in the body-in-white: D2: 334 parts →D3: 267 parts → D4: 243 parts. The body-in-white of the D4 contains:

- 144 aluminium sheet parts
- 33 steel sheet parts
- 25 aluminium castings
- 30 aluminium extrusions.

On the other hand, the number of the applied aluminium alloys increased (as well as their yield strength level):

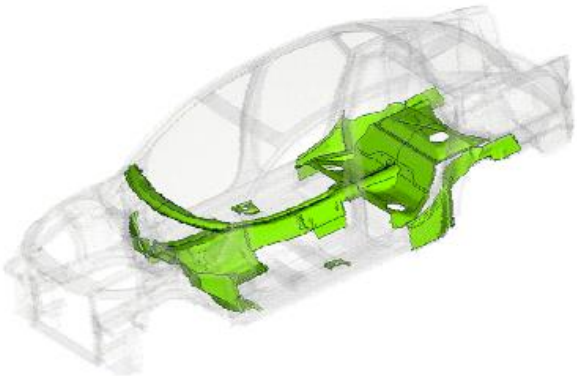
- D2: 7 alloys 100 – 200 MPa
- D3: 10 alloys 120 – 240 MPa
- D4: 13 alloys 120 – 280 MPa.

Also the amount of joining required for the production of the body structure could be reduced. Moreover thermal joining was reduced in favour of cold joining techniques. As an example, the newly introduced “Flow Drill Screws” replace nearly 40 m MIG welding. The joining techniques applied in the production of the D4 are:

- 1847 Self-piercing rivets
- 25 m MIG welding
- 6 m Laser welding
- 632 Self-cutting screws (“Flow Drill Screws”)
- 202 Spot welds
- 44 m Structural bonding.

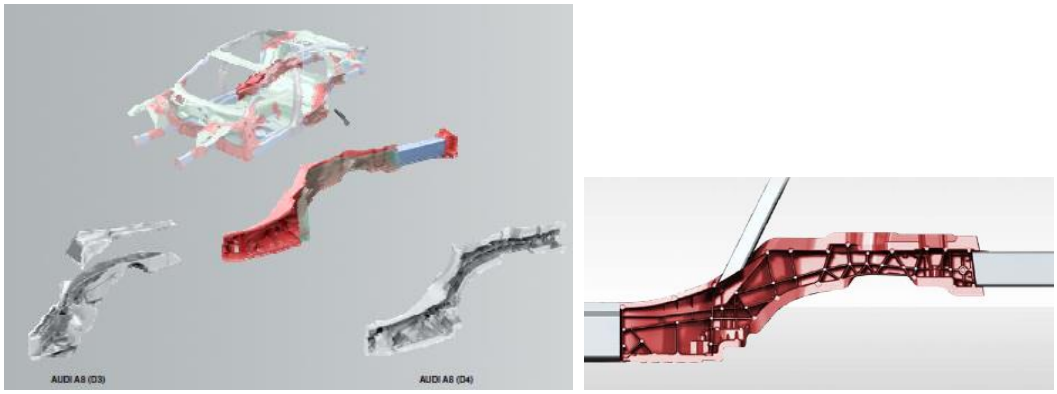
Aluminium spaceframe of the Audi A8 (D4)
(Source: Audi)

Other new developments include the introduction of new aluminium alloys. The substitution of a conventional AlMgSi car body sheet alloy in the body structure by the high strength Novelis Fusion AS250 material with a 20 % higher yield level reduced the vehicle by approx. 6.5 kg.



Applications of Novelis Fusion AS250 in the D4 model
(Source: Audi)

Also the trend towards large, multi-functional structural aluminium castings was followed up. The rear longitudinal beam includes a large casting (length 1.45 m) is a high pressure die casting using the alloy Castasil®-37 (AlSi9MnMoZr) which offers very high elongation in as-cast state.



Die-cast multi-functional sill/longitudinal member connecting element (Source: Audi)

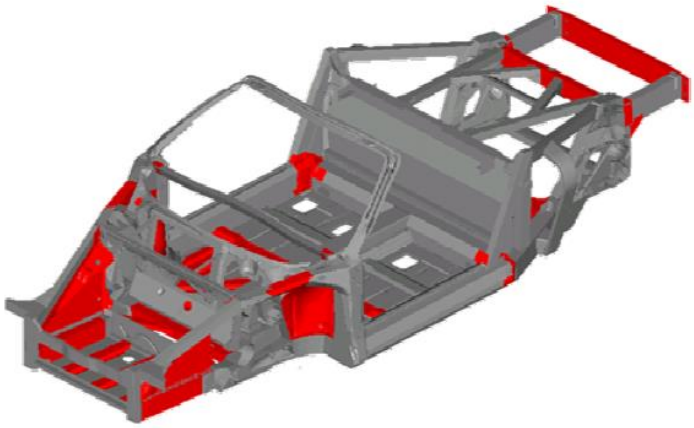
1.4.2 Ferrari – aluminium spaceframe design for niche volume production

The F360 Modena was the first Ferrari road car to feature a full aluminium body. The F360 model was a 2-seater mid-engine sports car built from 1999 to 2004. Ferrari partnered with Alcoa to produce an entirely new all aluminum space-frame structure that was 40% stiffer than the predecessor F355 which had utilized steel. The design was 100 kg (28%) lighter despite a 10% increase in overall dimensions resulting in greater comfort and storage space as well as a better weight to power ratio.

Aluminium spaceframe of the Ferrari F360 Modena (Photo: Alcoa)

The chassis was constructed from aluminium extrusions with varying cross-sections, welded together via cast aluminium nodes. This construction provided 40% greater rigidity. Twelve sand castings are incorporated in the lower part of the chassis, including the four suspension mountings. The shock absorber towers are CNC machined after assembly to ensure that the mounting points for the suspension components are drilled with absolute precision. The upper chassis structural assemblies are vacuum high pressure die cast to reduce their thickness. The aluminium alloy body panels are riveted to the chassis frame.

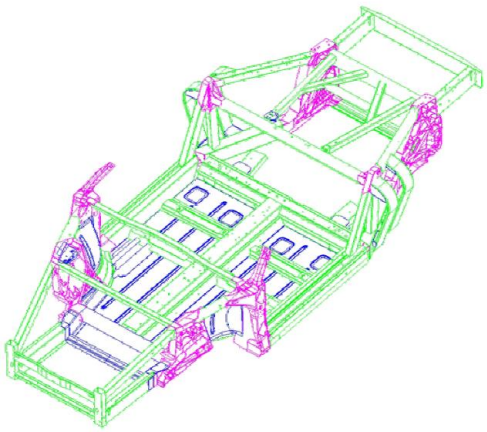
The F360 Modena was replaced by the F430 (produced from 2004 to 2009). Much of the extruded spaceframe of the F360 was carried over. Nevertheless, the stiffness and crash performance of the spaceframe could be significantly improved, amongst others by the implementation of a floor panel made from an ultra-high strength aluminium sheet.



Aluminium spaceframe of the Ferrari F430; red parts changed compared to F360 (Source: Alcoa)

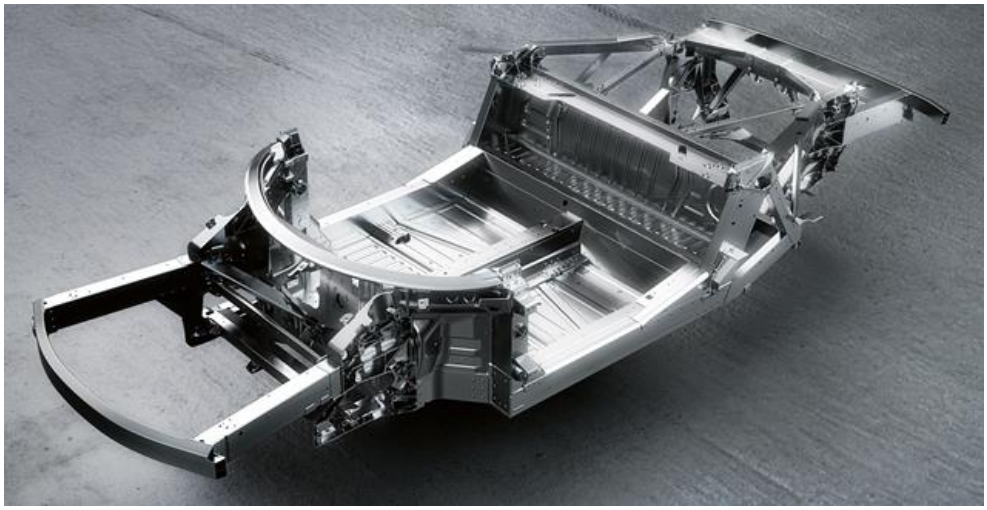
The spaceframe of the Ferrari F430 without bumpers, IP carrier and radiator support consists of 167 parts (65 extrusions, 12 castings and 90 sheet parts). The total weight is 165.4 kg:

- Extrusion 76.3 kg
- Castings 52.5 kg
- Sheet parts 27.5 kg
- Others 9.1 kg.



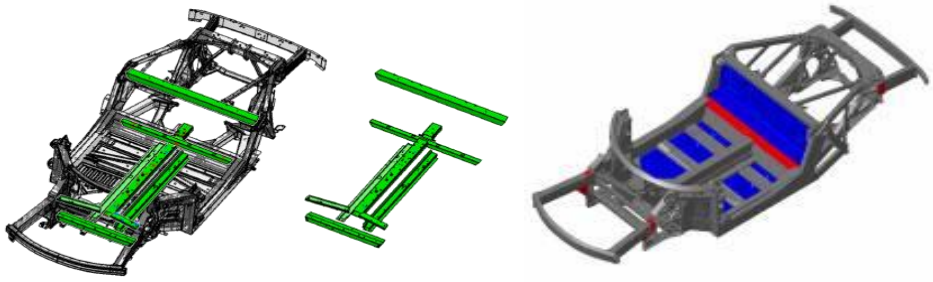
Aluminium product forms in the spaceframe of the Ferrari F430 (Source: Alcoa)

The Spider is 70kg heavier than the hard-top, due to a reinforced windscreen to protect occupants in the event of a rollover, internal strengthening of the doors to guard against side impacts and the electric motors which power the hood.
The F430 was followed by the Ferrari 458 Italia, presented in 2009. Like its predecessor, the 458 Italia has a mid-engine. The aluminium spaceframe body, however, has been redesigned.



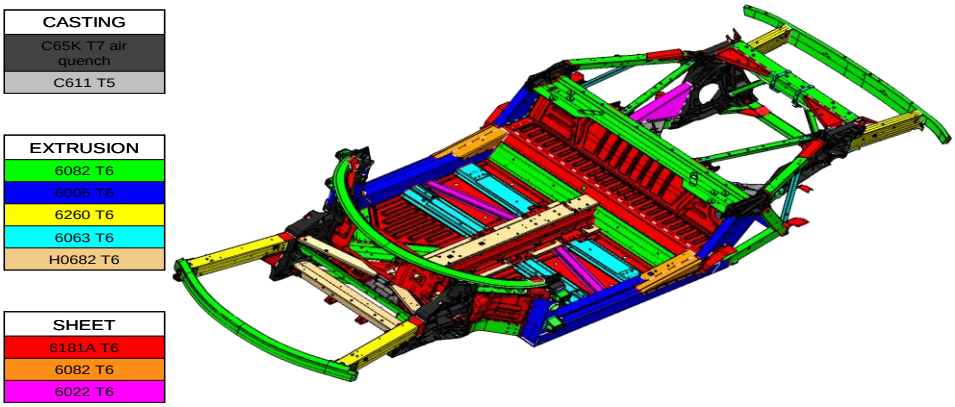
Aluminium spaceframe and body shell of the Ferrari 458 Italia
(Photo: Ferrari)

The introduction of new high strength alloys for both extrusions and sheet component enabled an increase of the mechanical design parameters by 80 % compared to the F430 spaceframe.



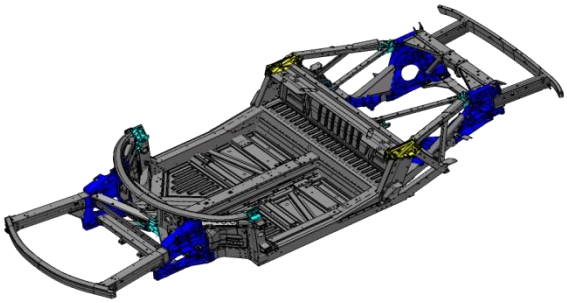
High strength alloys for extruded and sheet components
(Source: Ferrari)

Five different aluminium extrusion alloys are used (with yield strength of up to 320 MPa), allowing a reduction of the minimum thickness of the extrusions to 1.6 mm. Also the thickness of the inner structural sheet panels was reduced on average by 25 % compared to the F430. Three different sheet alloys are used; the thickness of the thinnest structural panels is just 0.9 mm. For the body shell, the alloys Anticorodal®-170 and Anticorodal®-600 are used (thickness 0.9 to 1.1 mm).



Aluminium product forms and alloys in the Ferrari 548 Italia spaceframe (Source: Ferrari)

For the large and medium cast components, produced by vacuum high pressure die casting and gravity casting, three different alloys are used.



Location of the cast aluminium components in the Ferrari 548 Italia spaceframe (Source: Ferrari)

Additional innovative approaches were taken for the improvement of individual parts. An example is the torque box, the diagonal reinforcement across the front of the foot well, behind the front wheels. It is a single, heat-formed component of the alloy EN AW-6082 with a wall thickness that varies between 3 and 6 mm. The finished part weighs 1.75 kg, which is 25 % lighter than the torque box on the F430. The engine cover is produced by superplastic forming (using a special quality AlMg alloy). The inner door frame on the 458 is a single, high pressure die casting (replacing an assembly of six stamped sheet and extruded parts used for the F430 inner door frame).
The Ferrari 458 is constructed using 70 m of welds and 8 m of adhesive bonding. Ferrari employs CMT (cold metal transfer) MIG welding, a lower-temperature form of MIG welding that causes less heat distortion than conventional MIG welding. In the recent past, all the welding was done by hand, but now it is 40% automatic, performed by robots.

Concurrent with the change from the F360 to the F430 model, the aluminium spaceframe design was also introduced into the second Ferrari model range, the sports cars with a 12-cylinder front engine.

Ferrari 612 Scaglietti

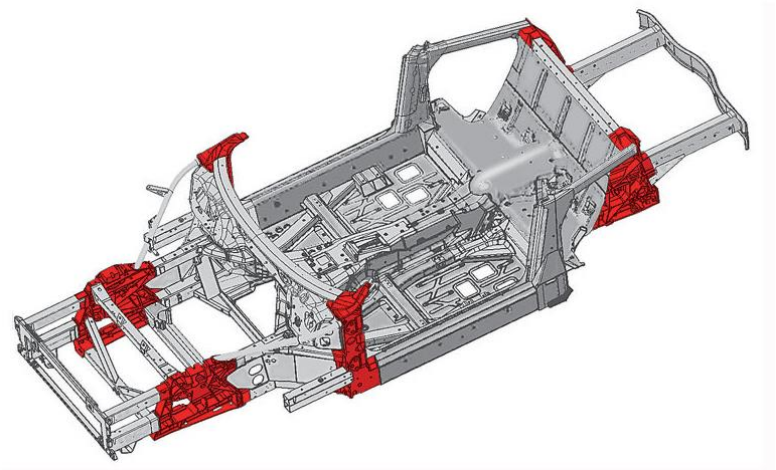
(Source: Ferrari)

The Ferrari 612 Scaglietti, a large two door 2+2 coupe produced between 2004 and 2010, was the second Ferrari all-aluminium vehicle. As on the F360 Modena, the structure consists of straight aluminium extrusions (38 %) connected by castings (34 %) which acts as joints. But the spaceframe design has been further developed in cooperation with Alcoa. In addition to the castings at the joints, there are also large castings at the front and rear to carry the suspension. Sheet aluminium (28 %) reinforces the structure. The structural aluminum panels are riveted in position, and the body shell aluminium panels added.

The all-aluminium construction cuts the car weight by 40 % and simultaneously increases the overall structural rigidity (rigidity-weight ratio) by 60 %. In addition to this, the 612 Scaglietti's near-perfect weight distribution (46 % front and 54 % rear) means that it offers both the high performance driving of a mid-engine car and the roomy versatility of a front-engine layout.

Aluminium body shell of the Ferrari 612 Scaglietti

(Source: Ferrari)

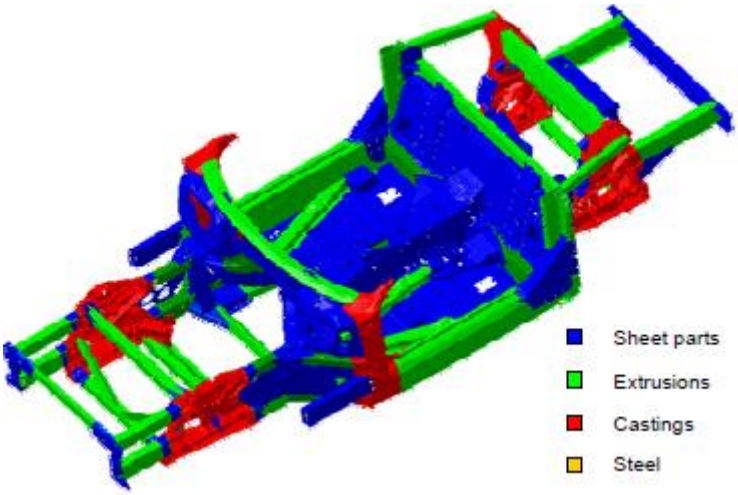


Spaceframe of the Ferrari 612 Scaglietti with large cast parts

(Source: Ferrari)

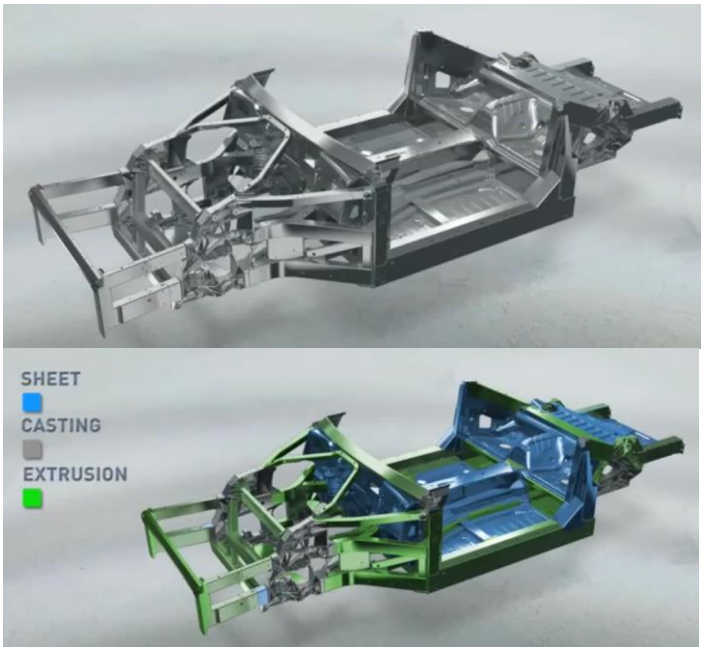
The chassis of the 612 Scaglietti also formed the basis of the 599 GTB Fiorano which was released in 2006. The 599 GTB Fiorano replaced the 550/575 Maranello and offered more interior space and power than its predecessors. As the 575 was the last Ferrari to use a steel chassis, it also completed Ferrari's change to all-aluminium models in the larger volume range. The aluminium lightweight design makes the 599's chassis 100 kg lighter than the 575 despite being 250 mm longer.

599 GTB Fiorano with its aluminium spaceframe
(Source: Alcoa)



Aluminium product forms in the Ferrari 599 GTB Fiorano spaceframe
(Source: Alcoa)

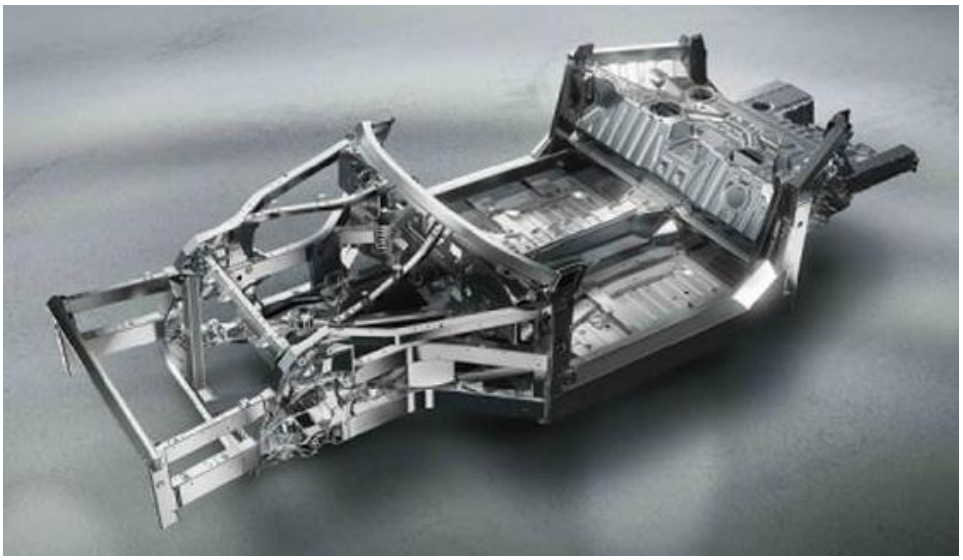
A similar design concept was used for the aluminium spaceframe of the Ferrari California, a two-door 2+2 hard top convertible released in 2008.



Aluminium spaceframe of the Ferrari California
(Source: Ferrari)

A thorough mid-life update in 2012 focused on the aluminium spaceframe of the California. Based on the experience collected in the production of the 548 Italia, weight saving of 30 kg could be achieved with no loss of rigidity by careful analysis of the entire structure and the use of 12 newly developed alloys instead of the 8 alloys previously used.

The 599 GTB Fiorano was replaced for the 2013 model year by the F12berlinetta (also referred to as F12 Berlinetta). Using the improved spaceframe concept of the 458 Italia, an all-new spaceframe chassis and body shell based on the use of 12 different kinds of aluminium alloys and the application of new assembly and joining techniques was developed.



Aluminium spaceframe of the Ferrari F12berlinetta
(Photo: Ferrari)

The result was a 20 % increase in structural rigidity while reducing the body weight by 50 kg compared to the 599 GTB Fiorano. The new chassis also meets all future safety norms (including side intrusion and roof roll-over protection).

Although Ferrari employs the carbon fibre reinforced plastic (CFRP) technology for manufacturing its formula 1 race cars and also extreme performance models F50 and Enzo, it believes that aluminium is better suited at production volumes of about 30 cars per day, at least for the foreseeable future. However, Ferrari anticipates that it will do more adhesive bonding than fusion welding in the assembly plant.

1.4.3 BMW - extrusion-intensive aluminium spaceframe designs

Extrusion-intensive spaceframe design concepts are specifically adapted for low volume production because of the relatively low cost of the extrusion tools and the high design flexibility.

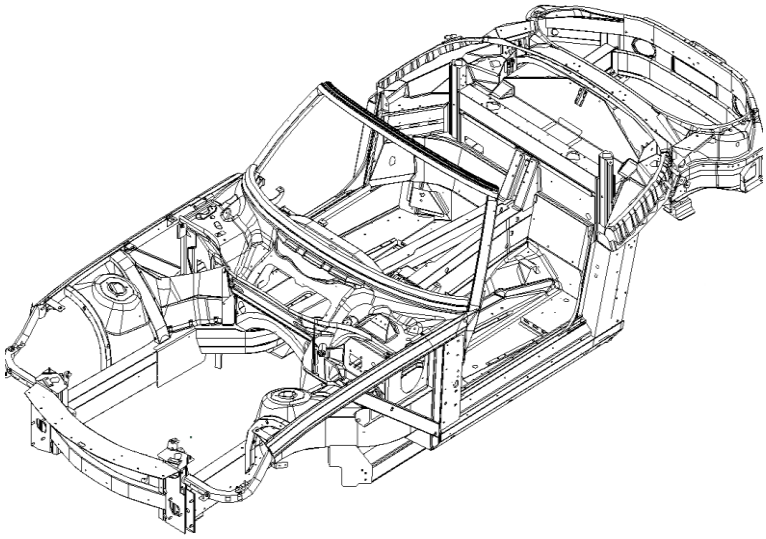
a) BMW Z8

A spaceframe design concept specifically adapted for low volume production was developed for the BMW Z8 (E52) roadster in cooperation with Hydro Aluminium. The Z8 was produced from 1999 to 2003. The space frame was made of extruded aluminium beams and panels, which reduce the body weight by 30 % compared with steel. The weight of the spaceframe structure was 230 kg, the total mass of the body-in-white 275 kg.

BMW Z8 roadster (produced from 1999 to 2003)

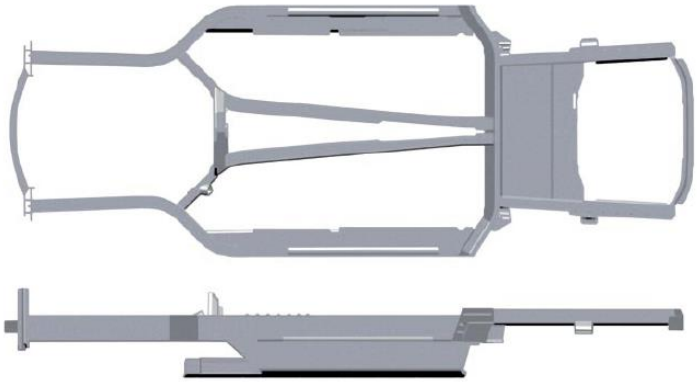
(Source: BMW)

The aluminium spaceframe structure included about 68 % extruded components and 32 % sheet panels (plus some steel rivets). Only straight and 2D-bent extruded beams were used. In case of the sheet panels, care was taken to choose simple shapes. In many cases, only folding of the sheets was necessary. 290 sheet parts, 86 straight and 24 bent extrusions and aluminium panels were joined by MIG welding and adhesive bonding plus riveting. The spaceframe was manually assembled using 57 m MIG welds and 890 self-piercing rivets.



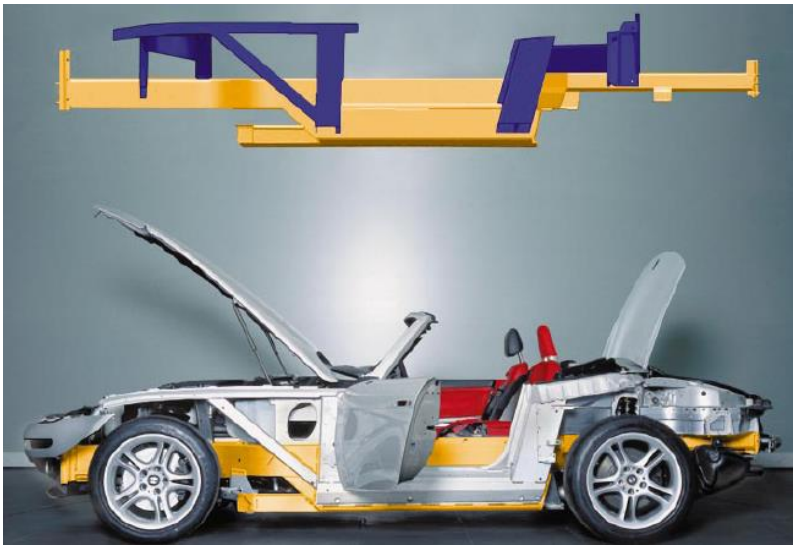
Aluminium spaceframe of the BMW Z8
(Source: BMW)

The stiffness of the central frame, made from properly designed hollow aluminium extrusions, allowed the application of much lower side sills than normally used for a roadster. The pairs of the unique aluminium Y arms that connect the front and rear sections provided much of the torsional rigidity. They also ensured an excellent crash performance. The front and rear arms were designed to crumple, absorbing energy and transferring forces to the sturdy centre floor pan.



Frame base structure of the BMW Z8
(Source: BMW)

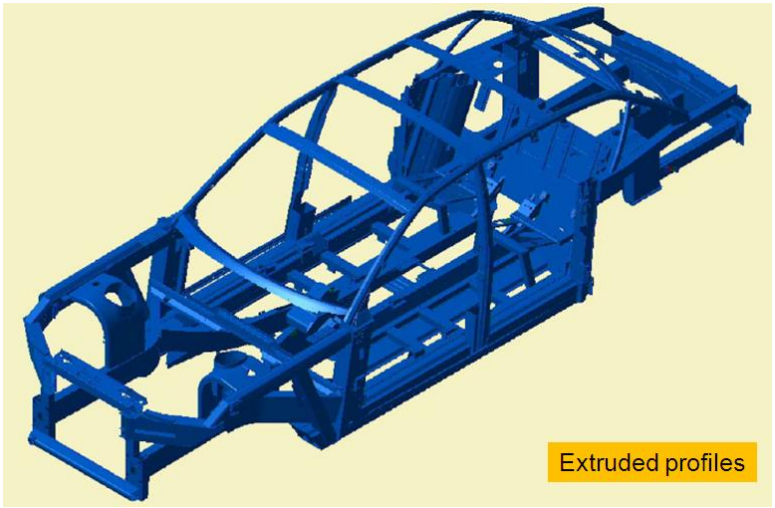
Depending on the specific application, the extrusion alloys EN AW-6060, 6063 and 6082 were used for the frame structure. For the structural sheets, the non-age hardening alloys EN AW-5754 and 5182 were chosen. In case of the closures, the alloy EN AW-6016 was used for the outer panels, for the inner panels EN AW-5754 or 5182.



Spaceframe of the BMW Z8 roadster (side view)
(Source: BMW)

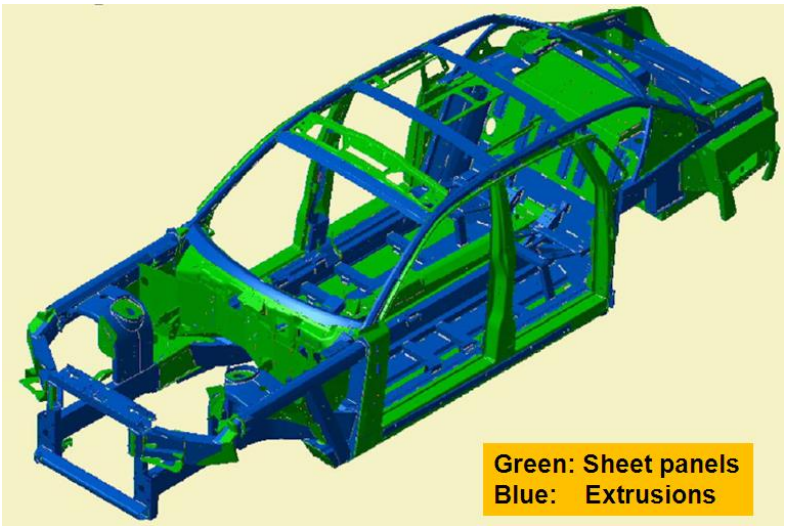
b) Rolls Royce Phantom

A similar aluminium body design concept was chosen for the Rolls Royce Phantom. The Rolls Royce Phantom is a saloon automobile made Rolls-Royce Motor cars, a BMW subsidiary. Launched in 2003, it is the first model introduced during the BMW era.
The Phantom's aluminium space frame is the largest of its kind ever built for automotive use. Made up of 248 extruded aluminium profiles and 278 sheet parts, it combines low weight with extreme strength. The complexity of the design was kept to a minimum; it contains neither 3D bent extrusions nor cast parts and as little as possible stamped panels. The whole body shell weighs just 550 kg yet has a torsional rigidity of more than 40,000 Nm/degree – making it at least twice as stiff as any previous Rolls-Royce.



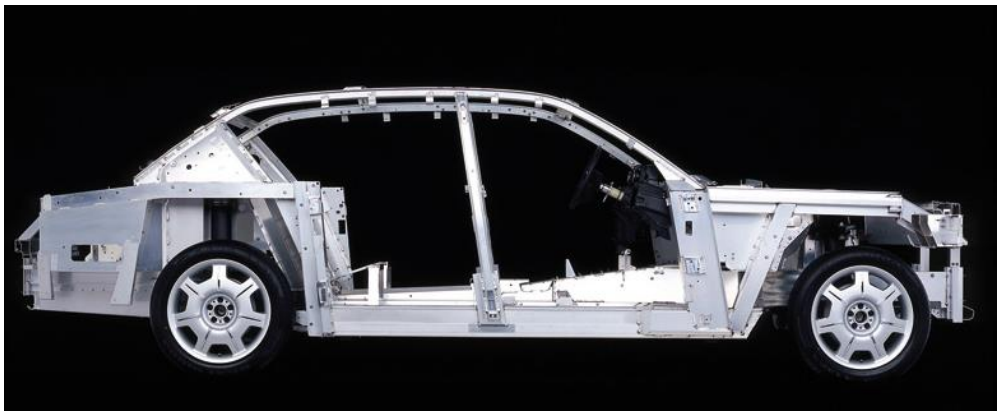
Extrusion-intensive spaceframe of the Rolls Royce Phantom
(Source: Rolls Royce)

For the extrusions, the alloys EN AW-6060, 6063 and 6082 in T5 or T7 were selected. The aluminium outer panels are EN AW-6016, the structural panels EN AW-5182 and 5454.



Aluminium product forms in spaceframe of the Phantom (Source: Rolls Royce)

Produced at BMW's Dingolfing plant, each frame has 120 m of welds at about 1800 separate locations, every one completed by hand. There are also 725 self-piercing rivets, 30 clinch points, 30 resistance spot welds, and about 90 blind rivets. The application of adhesive bonding was, however, avoided. State-of-the-art measuring equipment and CNC machining ensures that the entire body is constructed to within a plus / minus tolerance of just 0.1mm. Most exterior panels are aluminium, except the front wings (SMC) and the boot lid (steel). Some outer aluminium panels (e.g. the A and B pillar) are produced by superplastic forming in order to realize the required angular corners of the door opening. The door frames are built from sheet panels and Magsimal®-59 (AlMg5Si2Mn) castings.
The aluminium spaceframe was also used for the Phantom Drophead Coupe (launched in 2007) and the Phantom Coupe (SOP 2008). For the second generation Phantom, the spaceframe (SOP 2012) has been further reinforced with the addition of brace bars.



Aluminium spaceframe of the Rolls Royce Phantom (Photo: Rolls Royce)

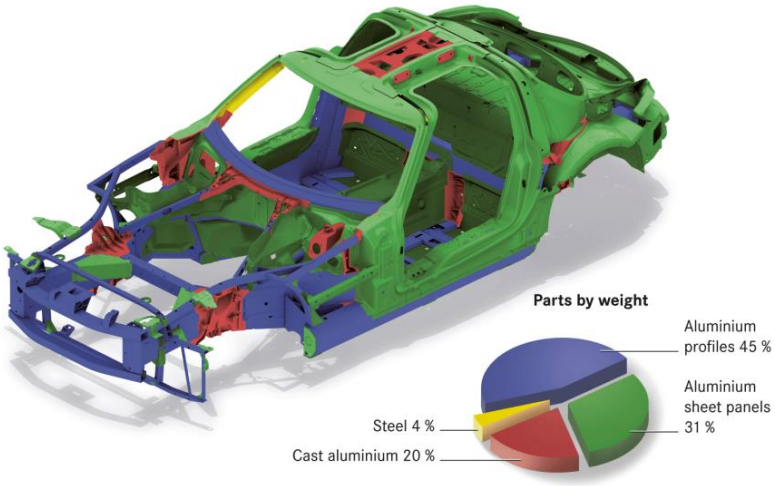
1.4.4 Mercedes-Benz – aluminium spaceframe design with large castings

The first car with an aluminium chassis and body of Mercedes-Benz was presented in 2009. Developed by Mercedes-AMG GmbH, a wholly owned subsidiary of Daimler AG, the SLS AMG all-aluminium body was produced by Magna-Steyr. The coupe version was followed in 2010 by the roadster and the in 2012 by the Mercedes-Benz SL (R231).

a) Mercedes-Benz SLS AMG and SLS AMG Roadster

The Mercedes-Benz SLS AMG is a front mid-engine, rear wheel driven coupe. Its newly developed body shell comprises an aluminium spaceframe combining intelligent lightweight design with outstanding strength and rigidity. The aluminium spaceframe with a weight of only 241 kg consists of cast aluminium components, extruded aluminium sections and aluminium sheet panels. Cast components are used at the nodal points where large forces must be transferred or where different functions must be integrated. Extruded aluminium sections connect the nodal points to a sturdy structure. The large cross-sections of these aluminium sections ensure high resistance torque. The resulting body structure ensures a high torsional rigidity and meets all the requirements in terms of passive safety. Maximum occupant safety requires the use of ultra-high-strength, heat-formed steel in the A pillars.

Aluminium spaceframe of the Mercedes-Benz SLS AMG (Photo: Daimler)



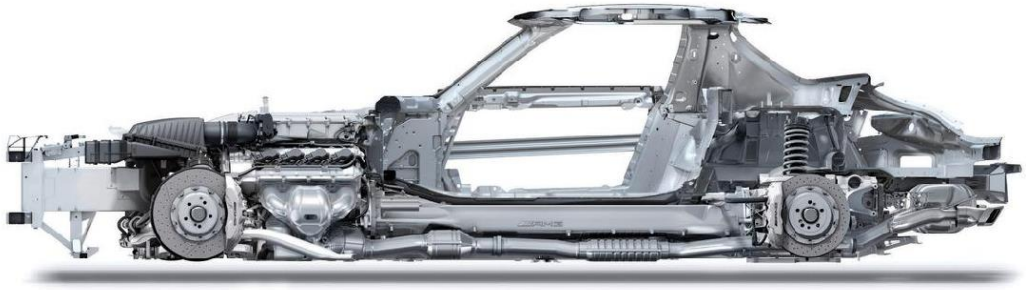
Material forms in the Mercedes-Benz SLS AMG spaceframe (Source: Daimler)

The aluminium spaceframe carries an equally lightweight outer skin: the bonnet, wings, doors and the side walls and roof are made of aluminium, while the front and rear aprons, side skirts and boot lid are of glass fibre reinforced plastic. The boot lid accommodates also the various aerial systems. The application of the superplastic forming technology for the gullwing doors made it possible to dispense with multi-part components, saving weight and simplifying the production process.

Cast components have the advantage of specific redirection of forces and allow a variation of the local wall thicknesses according to the encountered loads. Thus it is possible to incorporate areas of greater rigidity where required, for example at the chassis connections, or where large components such as the doors or dashboard are attached. The roof side member is an example; it carries the structural loads between the front and rear of the roof frame and also bears the hinges for the gullwing doors. Lightweight design by topology optimisation also helps to lower the vehicle's centre of gravity.

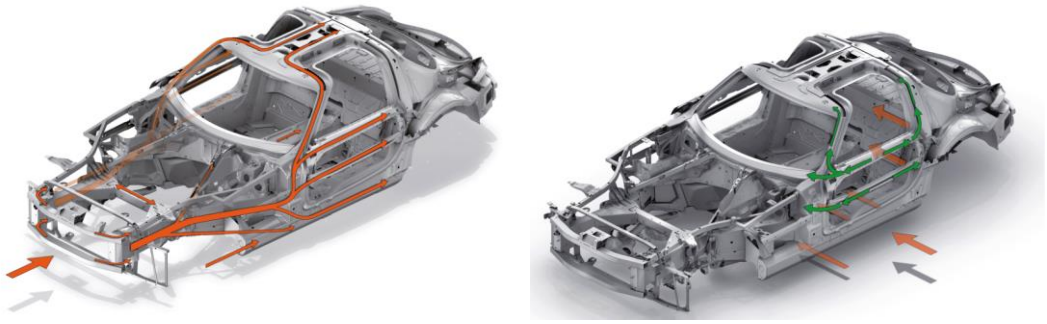
Cast aluminium parts in the Mercedes-Benz SLS AMG spaceframe
(Source: Daimler)

Other prominent features of the lightweight construction are the transverse reinforcing struts at the front and rear axles, which are integrated into the body shell structure. The sections connect the side members precisely where the highest forces act upon the body shell under dynamic cornering.
The SLS aluminium spaceframe consists of 16 cast parts, 146 extruded components and 197 sheet panels. The applied joining techniques include adhesive bonding, 975 self-piercing rivets, 581 self-threading screws (Flow Drill Screws) and 70.0 m CMT(Cold Metal Transfer) MIG welds.



Low centre of gravity – a key design priority
(Photo: Daimler)

The entire vehicle concept has been adjusted for the lowest possible centre of gravity. This applies both to the low connection of the powertrain and axles, as well as to the arrangement of body shell structure which has been kept as low as possible. Another design target was optimum occupant protection in all crash situations, including roll-over. This was achieved by directing the crash load paths around the strong and extremely rigid passenger cell.

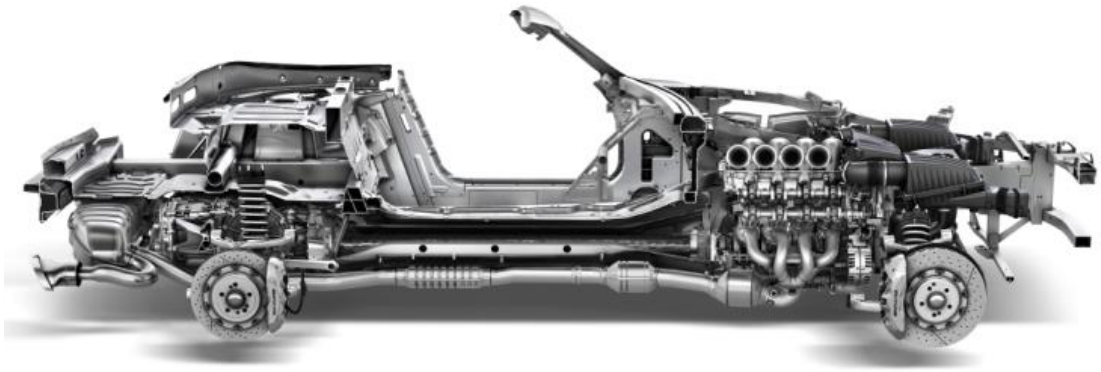


Crash load paths for front and side impact
(Source: Daimler)

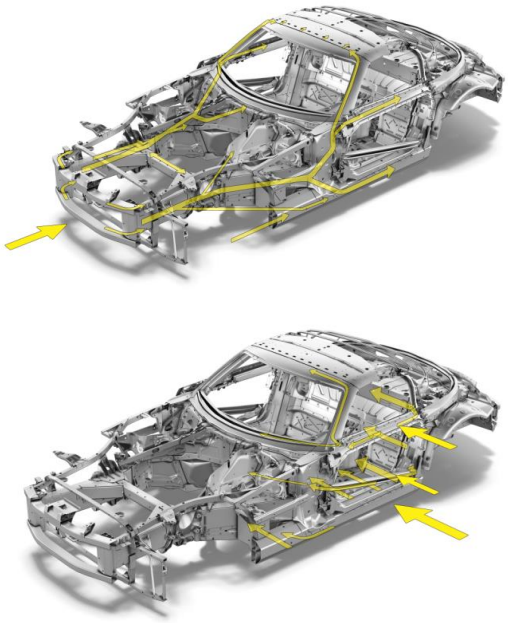
Since the roadster variant was already taken into consideration during the conceptual phase of the SLS AMG coupe, the weight of the body shell of the roadster (243 kg) is only 2 kg higher than that of the coupe version. Owing to the omission of a fixed roof and gullwing doors, it was necessary to design the side sills more robustly, i.e. side sills with greater wall thicknesses and chambers were chosen. In addition, the open-top SLS AMG has a reinforcing cross-member behind the seats which supports the fixed roll-over protection system.
In order to achieve handling dynamics identical to those of the coupe version despite the lack of a fixed roof, the roadster has two features designed to increase the rigidity of the body shell: the cross-member carrying the dashboard has additional supporting struts at the windscreen frame and at the centre tunnel, and a strut mounting stay between the soft top and the fuel tank makes the rear axle even more rigid. The side members of the front and rear modules in both SLS AMG models are identical.

Aluminium spaceframe of the Mercedes-Benz SLS AMG roadster
(Photo: Daimler)

The result is a slight variation of the different materials compared to the coupe: 50 % of the weight-optimised aluminium spaceframe is made of aluminium sections, 26 % of sheet aluminium, 18 % of cast aluminium and 6 % of steel. Maximum occupant safety is ensured by the use of ultra-high-strength, heat-formed steel in the A pillars. No changes were necessary with respect to the outer skin: the bonnet, wings, doors and side walls are of aluminium, while the front and rear aprons, side sill panels and boot lid are of glass fibre reinforced plastic. The three-layered fabric soft top of the SLS AMG Roadster is a weight-optimised, combined magnesium / steel / aluminium construction which ensures a low centre of gravity and still ensures the necessary stability for high speeds.



Aluminium spaceframe (side view)
(Photo: Daimler)



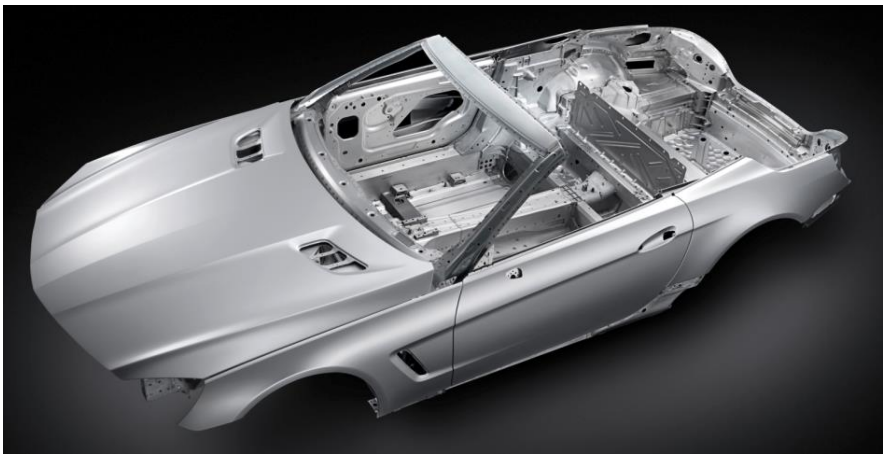
Crash load paths in the roadster variant for front and side impact
(Source: Daimler)

The new SLS AMG roadster also meets high passive safety standards. The specified lightweight construction and outstanding crash characteristics were designed to be in line with the car's low centre of gravity and the best possible distribution of load paths around the occupants – this applies to front, rear-end and lateral collisions, as well as to roof impacts. During a frontal collision, for example, the continuous side member extends from the front cross-member to the side skirt, and directs the impact energy into the extremely rigid structure of the door sill. As a result the passenger compartment remains undistorted during the usual frontal impact tests. One typical characteristic of the SLS is the front-mid-engine layout of the drive unit. This positioning behind the front axle provides a large deformation zone in front of the engine. This in turn allows a firewall of reduced weight, as it is required to absorb far less energy during a frontal crash than in a vehicle with a conventionally positioned engine.
Mercedes-Benz also offers an electric drivetrain in the upcoming SLS AMG E-Cell supercar. Power for the E-Cell will be provided by four electric motors. The E-Cell employs a permanent all-wheel drive system which is powered by a 400-volt battery made up of 12 modules of 72 lithium-ion polymer cells. The battery is housed in within the carbon fibre transmission tunnel, which is structurally integrated into the E-Cell's aluminium body shell.

Aluminium body shell of the Mercedes-Benz SLS AMG E-Cell
(Source: Daimler)

b) Mercedes-Benz SL (R231)

The new SL class model (R231) was formally launched in January 2012. It is the first series production, all-aluminium car of Mercedes-Benz. Its aluminium body structure weighs 257 kg, about 110 kg (or 24 %) less than it would using the steel body technology from the predecessor (R230). Also the number of parts which have to be assembled in the body shop could be significantly reduced from 496 (R230) to 339 (R231). At the same time, it was possible to increase the torsional rigidity by more than 20 % over the already very rigid preceding model. The “intelligent lightweight construction” is characterized by the use of components optimised for their specific tasks. Diverse processes are used to produce different kinds of aluminium components depending on their specific application: cast parts made by chill casting or vacuum die-casting, extruded aluminium sections or aluminium panels of different thicknesses.
The body-in-white of the SL (R231) is made from 89% aluminium, 8% steel and 3% shared between SMC (for the boot lid) and magnesium (for the tank cover). The A pillars and the roof frame are of steel sheet metal incorporating high-strength steel tubing. For these elements, steel proved to be the optimum solution to provide the required survival space for occupants in the event of the vehicle overturning with minimum reduction of the field of vision.



Aluminium body-in-white of the Mercedes-Benz SL (R231)

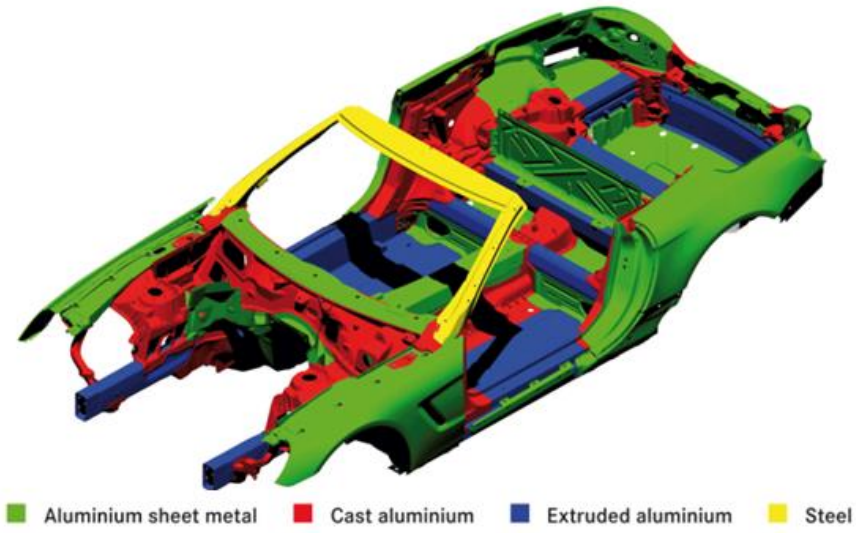
(Photo: Daimler)

The material product mix in the body structure of the SL model is dominated by aluminium castings. The cast-intensive approach offers significant cost advantages by component integration, but it also ensures a rigid design and package advantages.

	Number of parts	Weight
Al sheet panels	75	18 %
Al extruded sections	28	29 %
Al castings	33	45 %
Steel	16	8 %
total	**152**	**257 kg**

Material product mix in the body structure

(Source: Mercedes-Benz)



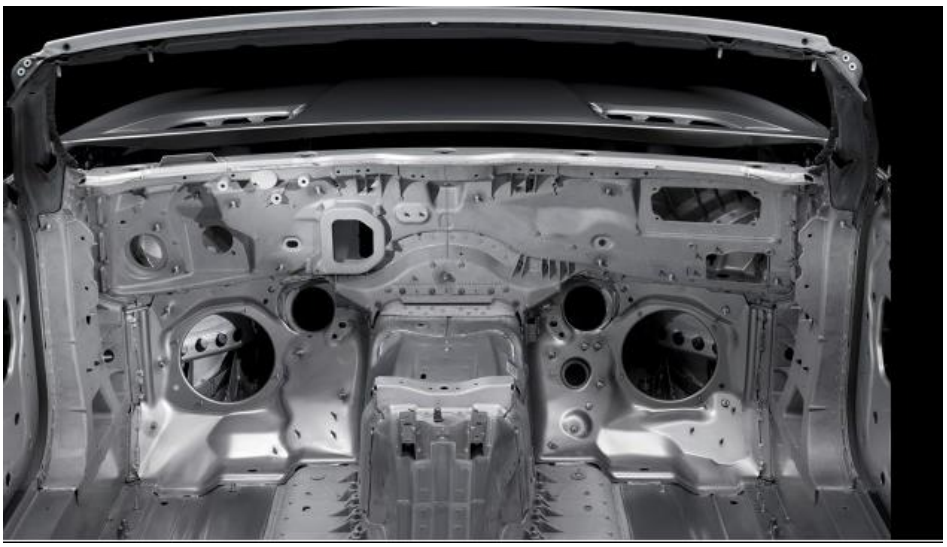
Material forms in the Mercedes-Benz SL (R231) body structure
(Source: Mercedes-Benz)

The SL body structure includes several innovative details:

- The longitudinal members in the vehicle front end are extruded aluminium profiles subsequently formed using the high-pressure hydroforming (IHU) technology. This enables the creation of highly complex components, permitting optimum use of the limited installation space.
- The door sills (longitudinal members) consist of 1.7 m long, seven-chamber extruded aluminium sections. Proper design of the cross section provides the required rigidity in the lateral sectors and sufficient energy absorption capacity in the event of a collision with a minimum component weight.
- The tunnel is made of an aluminium tailored welded blank of varying thickness. By using a tailored welded blank, it is possible to closely adapt the local sheet thickness to the forces exerted on the component under various loading conditions.

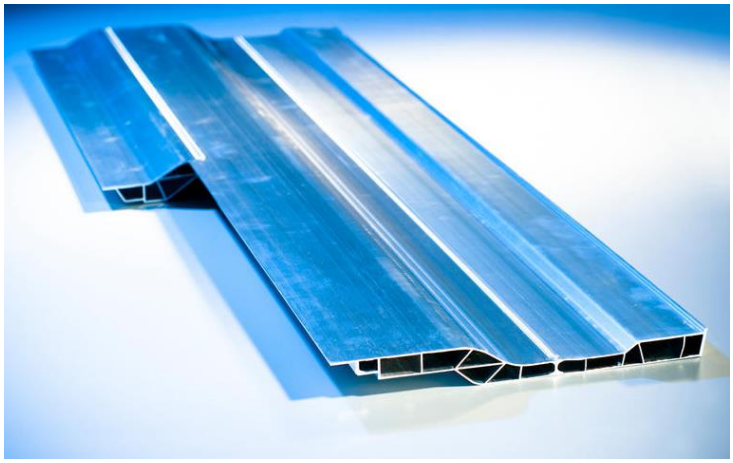
Tunnel made of aluminium tailored welded blank (joined by friction stir welding)
(Photo: Novelis)

- The front wall (upper firewall) is at present the largest aluminium cast component made in large series. The aluminium casting integrates six individual components into a single part.



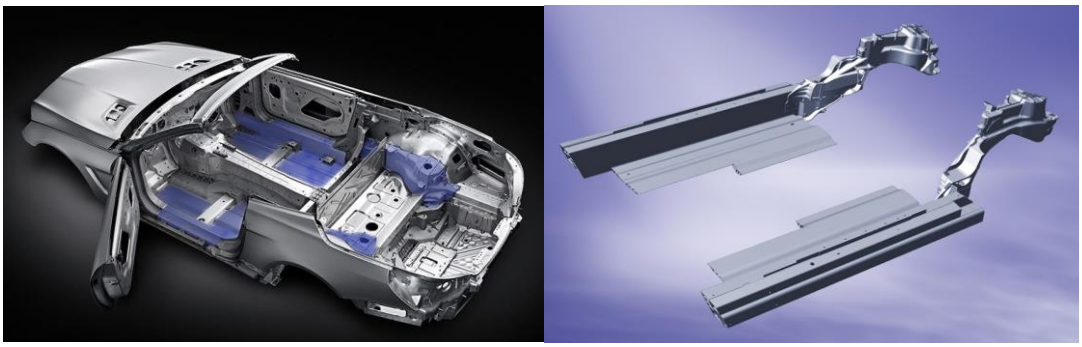
Upper firewall – a large vacuum high pressure die casting
(Photo: Daimler)

- The main floorpan is a three-layer, shaped panel made from thin, hollow extruded sections, which guarantees highest rigidity. The floorpan is welded together by friction stir welding.



Main floorpan – thin extruded aluminium sections joined by friction stir welding
(Photo: RIFTEC)

- The rear sector floor frame structure is closed by floor sheet metal panels and the boot tub made by vacuum high pressure die casting.
- The cast aluminium central member connects the front end with the rear sector floor. The mounting points for the drive shaft, the transmission cross beam, the transmission tunnel braces and the seat bolting points on the tunnel side are all integrated into a single element. The wall thicknesses and rib distribution are designed according to the specific load requirements.
- The rear sector floor is a MIG welded frame with a hollow cast longitudinal member as its central element. The low pressure permanent mould casting technique with sand cores is employed in the SL for the very first time in automotive body construction. The applied casting method and alloy (AlSi7Mg) ensure high strength with good ductility in the as-cast state and allow the realization of thick-walled areas without shrinkage cavity.
- A trunk floor panel made from “GreenAlu”, i.e. a sheet blank produced from a rolling ingot with a recycled content in excess of 90 %.



Aluminium floor structure of the of the Mercedes-Benz SL (R 231)
(Photo: Martinrea Honsel)

The assembly of the body-in-white is a highly automated (>95 %) and includes wide range of joining methods:

Joining technique	Number of joints or length of seal
Resistance spot welds	135
MIG welding	59.8 m
Friction stir welding	8.1 m
Adhesive bonding	76.2 m
Self-piercing rivets	1235
Clinch spots	213
Screws (incl. self-threading screws)	152
Tacks (ImpAcT)	14

Assembly of the R231 body-in-white (incl. supplied body components)
(Source: Mercedes-Benz)

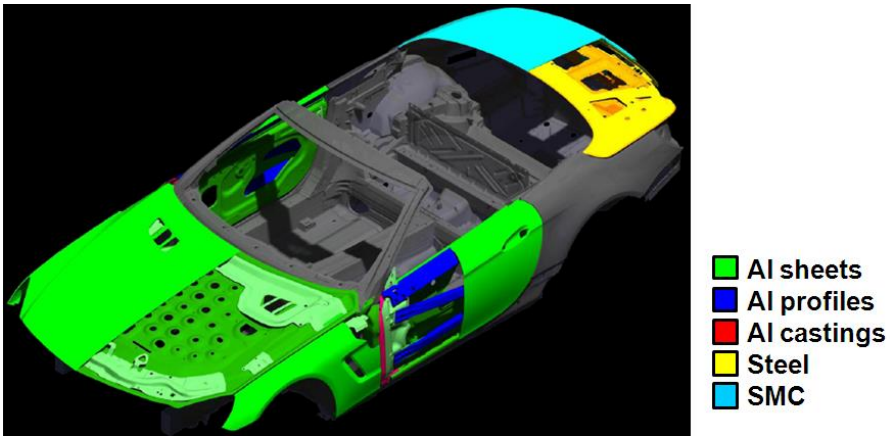
Most interesting is the replacement of some Flow Drill Screws (self-threading screws) by the “ImpAcT” (or RIVTAC® tack-setting) joining method. The tack-setting technique uses a nail-like auxiliary joining part which is accelerated to high speed and driven into the parts to be

joined. There is no need for pre-punching; the pointed tack just displaces the material. A necessary condition is that the joining parts are sufficiently stiff in order to sustain the penetration impulse of the tack without major deformation.

Joining technique	Body structure (%)	Hang-on parts (%)
Resistance spot welds	2	-
MIG welding	51	-
Friction stir welding	7	-
Adhesive bonding	19	56
Self-piercing rivets	17	28
Clinch spots	-	16
Screws (incl. self-threading screws)	3	-
Tacks (ImpAcT)	1	-

Joining processes used for the body structure and for hang-on parts (Source: Mercedes-Benz)

The high complexity of the assembly operation is the most remarkable difference compared to the fabrication of a conventional steel body-in-white. In case of the predecessor (R230), resistance spot welding was the dominating joining method (88 %), followed by adhesive bonding (7 %), self-piercing riveting (2 %) and others (3 %).



Material forms used for the hang-on parts (Source: Daimler)

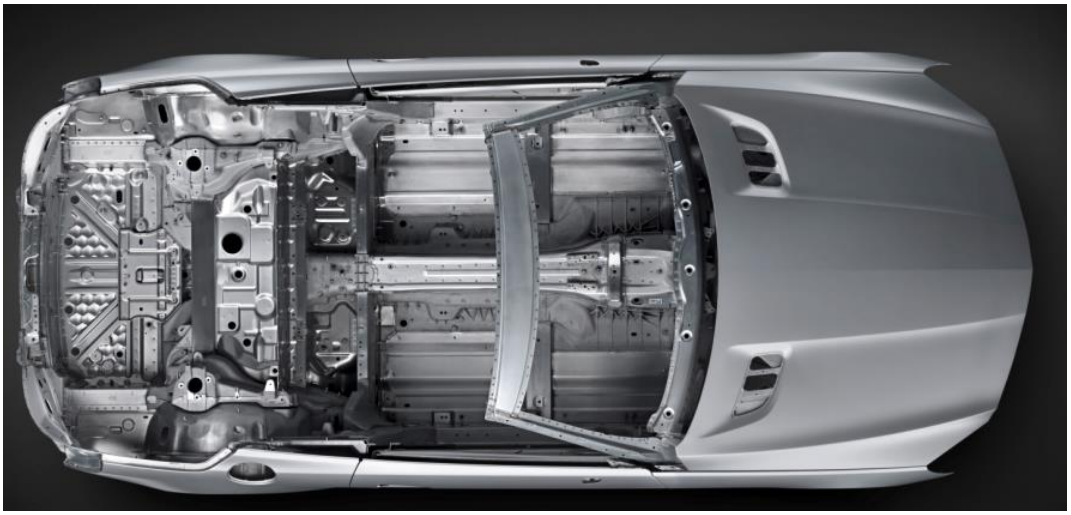
A range of materials are also used for the hang-on parts. The preceding SL model (R230) already had an aluminium bonnet, aluminium doors and aluminium boot lid. In the R231, the bonnet, doors and fenders are again aluminium. The doors are fashioned from a combination of sheet metal, extruded sections and cast metal parts, joined by diverse methods: riveting, bonding and hemming. Even the upper door hinges consist of aluminium (the lower hinges are made of steel). The “intelligent” material mix in the SL Body is completed by the boot lid, a hybrid design with an SMC (sheet moulding compound) outer and a steel inner panel. Both materials have virtually identical thermal expansion coefficients and complement each other very well. The interior steel construction ensures maximum rigidity with minimum use of space, while the plastic paneling allows the full integration of the various aerials.

	Number of parts	Weight
Al sheet panels	35	57 %
Al extruded sections	14	10 %
Al castings	2	5 %
Steel	6	19 %
SMC	5	9 %
total	**62**	**62 kg**

Materials used for the hang-on parts

(Source: Daimler)

Lightweight material solutions have been chosen also in other areas. The front module is a combination of an aluminium profile (for the bumper beam), aluminium sheet panels and glass fibre reinforced plastic. The rear bumper beam and crash boxes are aluminium extrusions. Die-cast magnesium components are used for the vario-roof structure as well as for the tank cover. The dashboard mount consists of an extruded and hydroformed aluminium tube with magnesium struts and moulded-on polymer brackets.
The new SL is also unique among the roadsters in terms of NVH comfort (noise, vibration, harshness). One contributing factor is a very rigid connection between the front section and rear floor. The higher sound emission and radiation level of aluminium compared to steel is compensated by means of a consistent sound insulation concept with targeted adaptation of the sound damping materials to each problem zone.

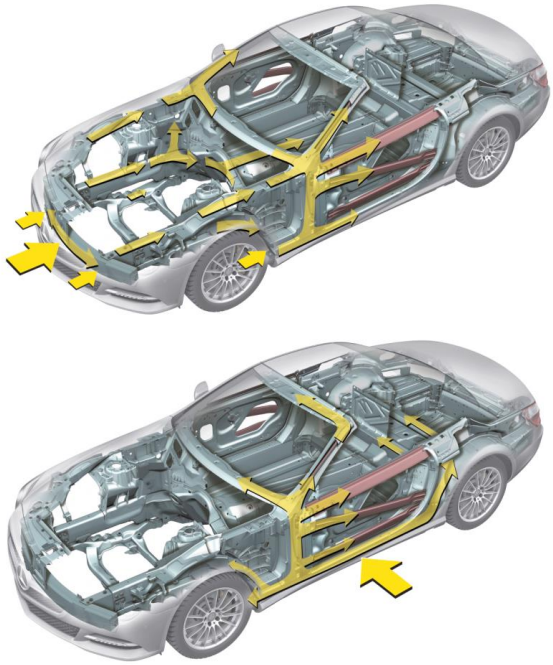


Aluminium body-in-white

(Photo: Daimler)

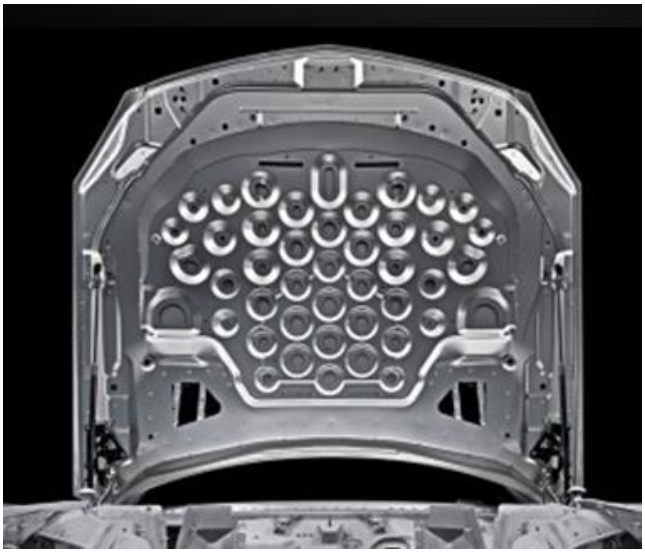
The new Mercedes-Benz SL sets new safety standards for roadsters. The chosen design concept ensures a very low centre of gravity. Furthermore, the aluminium body shell offers excellent preconditions for a highly stable and rigid occupant cell as well as for precisely defined deformation zones. The extruded sections, cast nodes and a double-thickness floor plate form a sturdy passenger compartment. The tail end and front are designed in such a way that they can absorb high forces through deformation, thus considerably reducing the strain on the occupants in a crash in accordance with the principle of the crumple zone. The

crash boxes behind the bumper trim and an exchangeable front module ensure that the damage sustained during a front impact at up to 15 km/h is limited.
A-pillars in a steel/aluminium material mix and two roll-over bars protect the passenger compartment in case of an overturn. Normally the two roll-over bars are completely recessed, but two preloaded pressure springs per cartridge ensure that the roll-over protection shoots to the support position in fractions of a second. Two aluminium sections in each door together with the very rigid side sills provide the greatest possible survival space in the event of a side collision.



Crash load paths in the SL roadster for front and side impact (Source: Daimler)

The new SL class roadster uses the latest technology in the area of pedestrian protection. A sensor system is able to register an impact with a pedestrian and ensures that the bonnet is immediately raised by 85 mm in the rear, creating additional space between the bonnet and hard components in the engine compartment. Also the deformation properties of the bonnet have been designed to meet the requirements concerning pedestrian protection. It was optimized in terms of form and materials, contributing towards the outstanding pedestrian protection. The SL's "soft nose" also provides a large impact area, whilst the foam density and geometry in the front bumper have been optimized for reduced loads during leg impact with the pedestrian.

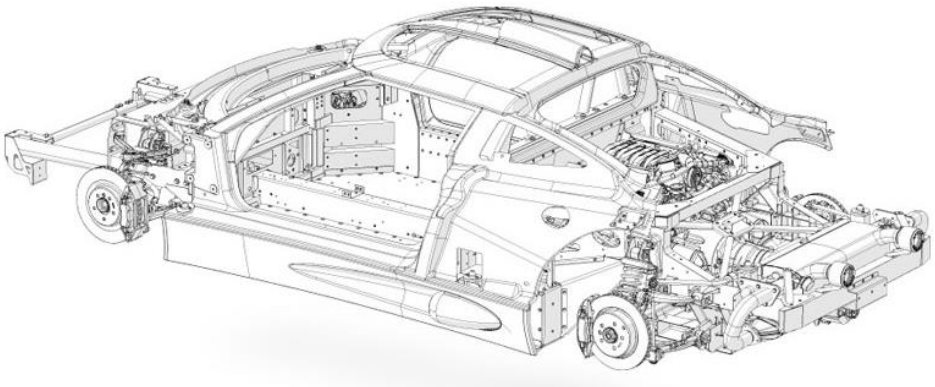


Aluminium bonnet design optimized for pedestrian protection

(Photo: Daimler)

1.4.5 Spyker – all-aluminium niche models based on a spaceframe design

Since the year 2000, Spyker produces exclusive mid-engine sports cars in very small numbers (< 100 per year) with an all-aluminium lightweight riveted body. The Spyker models feature an aluminium spaceframe chassis with an integrated roll cage and hand-beaten aluminium body panels. The chassis of the C8 is built from extruded aluminium box sections and folded aluminium sheets which are manually welded together.
Designed from the outset to be a roadster, the chassis stiffness shows little difference with or without the roof. The high rigidity of the chosen design and a pair of very strong and thick A pillars mean that the car does not need a windscreen header rail. Another specialty are the "butterfly" doors which swing upward and outward around a single hinge to open. As a result of the lightweight construction, the C8 model (with a V8 engine) weighs only 1250 kg.
The spaceframe of the Spyker C8 Aileron (presented in 2009) is a development of the original space frame. Modern finite element and numerical optimization methods have allowed an increase of the torsional rigidity by 40% without adding any weight. Also the dimensions have been changed; the wheelbase was increased by 10 cm for improved road handling and more cockpit space.



Aluminium body concept used by Spyker
(Source: Spyker)

1.5 Cars with an aluminium chassis and a separate body shell

Apart from the aluminium sheet unibody (or monocoque) design and the aluminium spaceframe, there are also novel aluminium-based lightweight body architectures which offer unprecedented design flexibility, in particular for small volume production (niche models). One possibility is the combination of an aluminium chassis with a separate body shell. The separate body shell can be produced from aluminium, but also other materials (preferably glass or carbon fibre reinforced plastics).

Efficient low volume production concepts are characterized by functional modularity and low investment needs in terms of manufacturing equipment as well as tools. Preferred aluminium components are straight or 2D bent extrusions, simple sheet parts (e.g. produced by bending and folding or shaped using forming technologies with low tool costs, e.g. superplastic forming), sand castings, etc. The structural components are MIG welded or joined with mechanical fasteners, sometimes combined with adhesive bonding.

1.5.1 Lotus platforms for low volume vehicles

With the development of the Elise, Lotus pioneered a new way of designing cars. The aluminum-tub chassis of the Elise was actually the first part of the Lotus “Versatile Vehicle Architecture (VVA)”. The same basic chassis has been later advanced for larger vehicles.

a) Lotus Elise

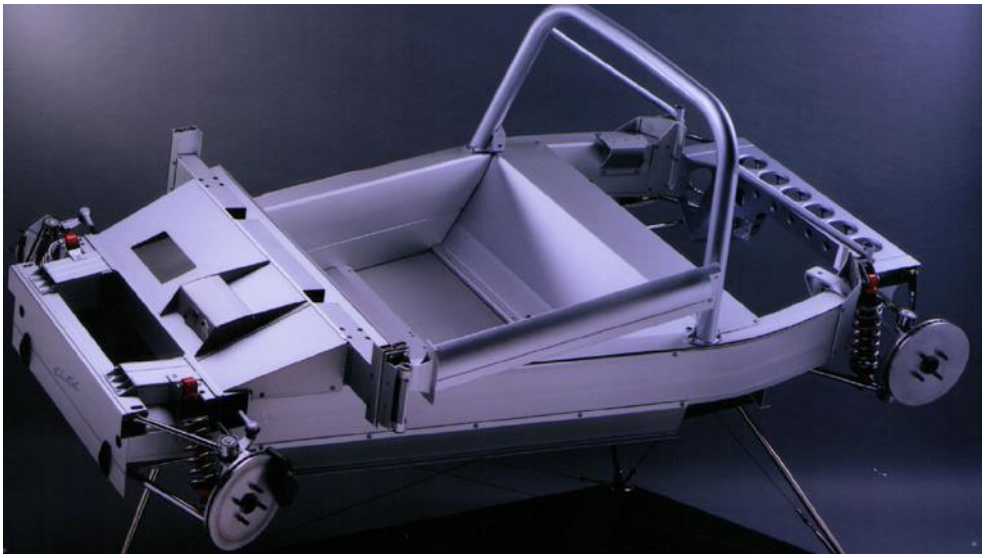
The Lotus Elise is a rear-wheel drive roadster with two seats and a mid-engine which was released in 1996. The car has a hand-finished fibreglass body shell atop an extruded aluminium chassis that provides a rigid platform for the suspension, while keeping weight and production costs to a minimum. The aluminium chassis was developed together with Hydro Aluminium.

Aluminium chassis of the Lotus small car platform (Elise)

(Photo: Lotus)

The aluminium chassis of the Elise (total weight 68 kg) is an extrusion-intensive design with only about 10 % sheets (by weight). It consists of 63 straight and 2 bent extrusions as well as 5 sheet panels.
The aluminium components are joined by adhesive bonding, supported by more than 130 self-tapping screws. Adhesive bonding eliminates the distortion that may come with welding. The applied adhesive is a single-part, heat-cured epoxy paste (XB 5315) from Ciba Polymers. Each joint is reinforced by EJOT self-tapping steel screws to prevent the onset of peel during a crash. The assembled chassis is then loaded to an oven where adhesive curing takes place at 200 °C (curing time about 40 min).

The applied extrusion alloy is EN AW-6063, the sheet alloy EN AW-3105. The durability of the adhesive bonds is ensured by a proper surface pre-treatment (anodization) of the extrusions. Both the design of the extrusions and the design of the chassis are specially adapted to the bonding process. Many of the extrusions link to the neighbouring extrusion with a tongue-in-groove joint. Also, where parts have to come together, the design ensures wide flat areas for the bonded joint. Furthermore, the outlines of the extrusions feature small ridges along all mating surfaces to control the gap width to prevent that the adhesive is squeezed out.
The aluminium chassis is completed with a steel roll-over bar. The body shell is made of composite body panels with detachable front and rear clamshells.



Chassis of the Lotus Elise
(Photo: Lotus)

Over the years, the aluminium tub chassis has changed only in detail. The Elise's structure, which includes a composite energy-absorbing front crash structure, is tough enough to meet all crash standards.
The modular aluminium chassis of the Elise ("Lotus small car platform") has been also used for various Lotus models (e.g. Exige, Europa S, 2eleven) and for third party vehicles (e.g. Opel Speedster (VX220), Tesla Roadster or Melkus RS2000). Also the Zytek Lotus Elise, a sports car with an electric drivetrain produced from 1989 to 2003, used this aluminium chassis.

Lotus small volume (Elise) platform

(Photo: Lotus)

b) Lotus Evora

The "Versatile Vehicle Architecture (VVA)" approach has been designed to be applicable to low and mid-volume applications by utilising low capital investment manufacturing processes. It progresses the Lotus technology from the Elise family of vehicles, using bonded extrusions

and folded panels, allowing its application for a range of vehicles up to a vehicle weight of 1,900 kg.
The Lotus Evora was launched in 2009. It is a 2+2 rear mid engine, rear wheel driven sports car. The modular design of the aluminium chassis offers improved manufacturability and easier repair.

Lotus Evora with an extrusion-intensive aluminium chassis

(Photo: Lotus)

The front subframe and the tub module are bonded and riveted (using self-piercing and blind rivets), For the front subframe, extrusions with 8 different cross-sections are used, the tub module includes extrusions with 20 different cross-sections. The extrusion alloy is EN AW-6060; the sheet alloy is EN AW-5754. The seat belt anchorage frame and the rear subframe are made of steel. However, the rear subframe could also be welded extrusions.

Extrusion-intensive aluminium chassis of the Lotus Evora

(Photo: Lotus)

The VVA architecture has been designed so that it can be stretched in width, length and height. The strength and stiffness of the low volume VVA chassis can be modified by varying the wall thickness of the extrusions, without altering the exterior dimensions. Front and mid engine installations have been considered, as well as hybrid and electric vehicle (EV) applications.

The VVA chassis uses advanced assembly techniques, including adhesive bonding, self-piercing rivets and flow-drill screws for its construction. The self-piercing rivets and the flow-drill screws (used for single-sided access on closed sections) hold the structure together during the bonding cure cycle, and prevent adhesive joint peeling in the event of a crash. The heat-cured high strength structural adhesive is the main joining medium. Used in combination with the mechanical fasteners, it produces a strong, durable joint and a lightweight shell with exceptional torsional stiffness.

Versatile Vehicle Architecture: Evora platform

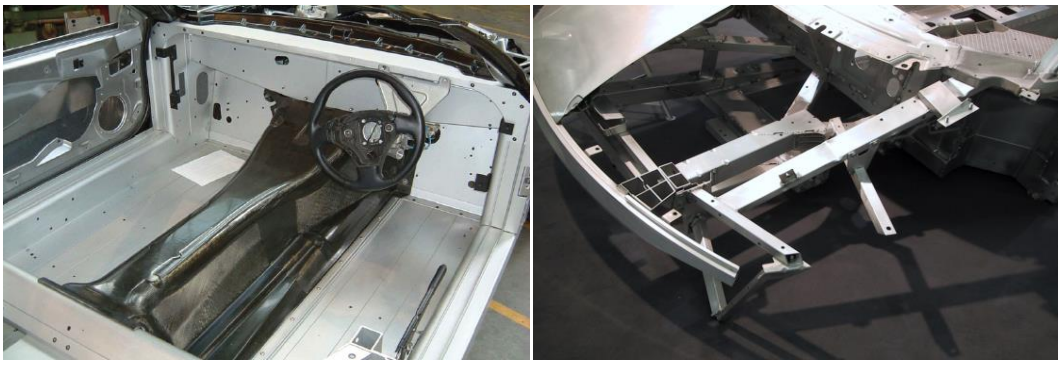
(Photo: Lotus)

The separate front subframe enables its replacement in the event of accident damage when suffering a frontal impact or when the suspension mounting points become damaged. Also the front bumper beam can be separately replaced if required after a minor frontal impact. The centre section essentially determines the global vehicle torsional stiffness. At the rear, the separate steel rear subframe with detachable bumper facilitates crash repair as at the front. During vehicle assembly, the engine transaxle and rear suspension and exhaust system are all assembled to the rear subframe before this completed module is offered up to the aluminium centre section. The rear subframe can be also fabricated from welded aluminium extrusions.

1.5.2 Aston Martin's aluminium VH platform

Lotus' influence extends to Aston, for whom the company consulted in the development of its Vanquish model, manufactured from 2001 to 2004. Aston Martin employed basically the same chassis technology as that used in the Lotus Elise, i.e. an extrusion-intensive aluminium tub chassis.

The main body structure of the Aston Martin Vanquish, a two door 2+2 coupe, included a combination of extruded aluminium sections and folded aluminium panels which were adhesively bonded and riveted. The aluminium tub was then bonded to a central carbon fibre reinforced plastic transmission tunnel. Carbon fibre A pillars, an all-aluminium suspension and aluminium body panels served to keep weight down. The stiff aluminium/carbon composite construction chassis was completed with a composite front and rear crash structure and superplastically formed aluminium as well as composite outer panels.



Aluminium chassis and carbon transmission tunnel joined by a structural, hot curing adhesive (left) and aluminium front structure (right)

(Source: Aston Martin)

The finished aluminium chassis had a weight of 145 kg, it consisted of 40 straight extrusions with a total weight of 100 kg and 40 sheet panels (total weight 45 kg). 176 rivets and 76 self-threading screws were used for assembly.

Aluminium/composite chassis of the Aston Martin Vanquish V12
(Source: Aston Martin)

The aluminium chassis of the original Aston Martin Vanquish evolved into the VH (for vertical/horizontal) platform that would go on to underpin all future Aston Martins (except for the One-77 which uses carbon architecture and the Cygnet). At the time it was not considered to be a VH platform, but in retrospect it should be treated as one.

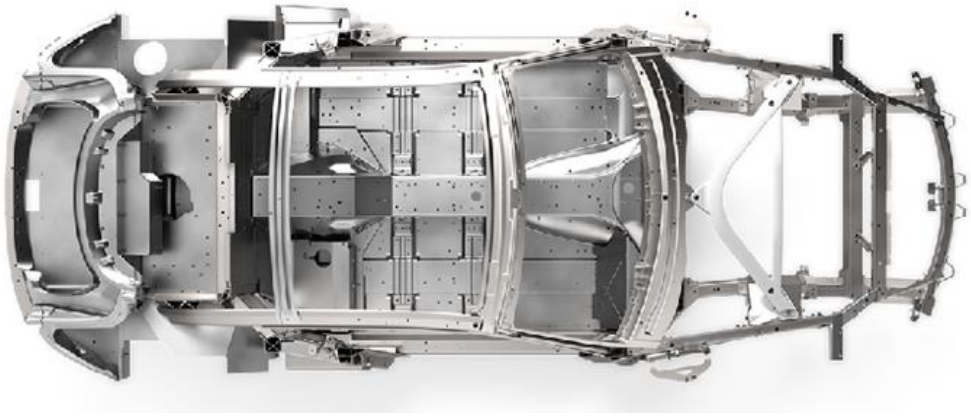
The Aston Martin 2+2 DB9 coupe (released in 2004) featured the first official all-aluminium VH platform with an aluminium/composite body. The outer body panels are not structural, i.e. the VH platform allows for inexpensive restyling of future models.

Aston Martin DB9

(Source: Aston Martin)

Drawing on the experience and technology pioneered in the Vanquish, the DB9's frame is made entirely from aluminium. Die-cast, extruded and stamped aluminium components are adhesively bonded, supplemented by mechanical fixing using self-piercing rivets. Despite being 25 percent lighter than the steel body shell of the preceding DB7, the DB9 structure has more than double the torsional rigidity.

The adhesive is applied by a robot; computer controlled hot-air curing ensures high bonding accuracy and repeatability. The aluminium frame is the skeleton to which all the mechanical components are either directly or indirectly mounted. The body panels are then fitted to the frame, again using adhesives. The bonnet, roof and rear wings are aluminium. The front wings and boot lid are composite. Cast aluminium is used in the windscreen surround. Magnesium is used in the steering column assembly and inner door frames. The driveshaft is made from carbon fibre reinforced plastic.



Top view of the aluminium chassis of the Aston Martin DB 9

(Photo: Aston Martin)

The bonded aluminium chassis of the VH platform was also used for the Aston Martin V8 Vantage and its variants as well as the Aston Martin DBS presented in 2007. The DBS became the first production Aston Martin to make extensive use of carbon fibre reinforced plastic body panels. Carbon fibre panels are used for the boot enclosure, boot lid, door opening surrounds, front wings and bonnet, resulting in a weight reduction of 30 kg over the conventionally used aluminium panels without any reduction in strength.

Aston Martin's all-aluminium VH platform with an aluminium/composite body

(Source: Aston Martin)

The third VH chassis is used in the Aston Martin Rapide. It differs from the first two generations as it is longer to accommodate the longer four door body. The Aston Martin Rapide is a four-door, high-performance sport saloon which was introduced in early 2010. The Rapide shows the same extruded, bonded, and riveted aluminum chassis construction as the earlier DB9 models, although it is larger than any model previously adapted from the VH architecture.

Body structure of the Aston Martin Rapide
(Source: Aston Martin)

The new Aston Martin Vanquish (2012 -), the fourth generation of the VH platform, uses even more carbon fibre in its design than previous VH chassis.

1.5.3 Morgan – a sheet-based aluminium chassis

The Morgan Aero 8 sports car (2001 – 2010) was the first Morgan vehicle with an aluminium chassis and frame as opposed to traditional Morgan vehicles that had an aluminium skinned wooden body shell on a steel ladder frame chassis.
Manual fabrication of small production volumes led Morgan to look for a design with minimum tooling cost. Consequently, Morgan developed an aluminium chassis structure built mainly from flat aluminium sheets, but reinforced by extrusions for cross members and longitudinal members. The stiff, lightweight chassis consists of 32 aluminium alloy panels which are adhesively bonded and riveted. The aluminium alloy sheets are especially surface pre-treated and then bonded with Gurrit Essex adhesive (a technology developed by Alcan). For riveting, self-piercing Boellhoff rivets are used. An ash frame is then mounted on the aluminium chassis which carries the aluminum body panels.
The Aero 8's unique construction consisting of an aluminium chassis, combined with the traditional Morgan ash wood body shell and superplastically formed aluminium outer panels make it a very strong, but also very light open top car. The same design concept is also used in Morgan's current car models (e.g. Morgan Plus 8).

Aluminium chassis of the Morgan Aero 8
(Photo: Morgan)

Morgan Plus 8 with an aluminium chassis and aluminium outer panels on a wood frame
(Photo: Morgan)

1.5.4 Chevrolet Corvette

In the Corvette Z06 (start of production 2006), the steel frame of the conventional C6 was substituted by an almost identical aluminium spaceframe, thereby reducing the mass by over 30 %. The spaceframe engineered by Dana Corporation, was completed with glass fibre reinforced plastic body panels.
The spaceframe, consisting of 90 aluminium components (21 extrusions, 8 castings, and 61 sheet stampings), also leads to a reduction in the overall number of parts used. The one-piece, hydroformed perimeter frame with cast suspension nodes is made from a 4.8 m long, extruded EN AW-6063 tube (weight 24 kg). The standard C5/C6 steel frame is 3 mm thick and weighs 228 kg, while the Z06 aluminium frame is 4 mm thick and weighs only 178 kg, but shows a 50 % higher bending and torsional stiffness. The EN AW-6063 frame rail is heat treated to the T7 temper; because of the resulting excellent combination of strength and elongation provide outstanding crashworthiness.
EN AW-6063 alloy extrusions are also used for the bumper reinforcements, the A pillar, and the roof reinforcement bar. In addition, there is an EN AW-6061 T6 extruded seatback beam.

Stamped aluminium panels are used for the B pillar assembly and the construction of the floor and tunnel (made from annealed 4 mm thick EN AW-5745 sheets). A356 aluminium castings are used for the front and rear suspension-mounting locations.

The Z06 aluminium structure is held together by MIG and laser welds as well as self-piercing rivets. Laser welding is used specifically in the tunnel area, there are in total 14 m of laser welds (which equates to nearly one-third of the frame's welds). 236 self-piercing rivets are used for assembling some stamped pieces together, for example the B pillar.

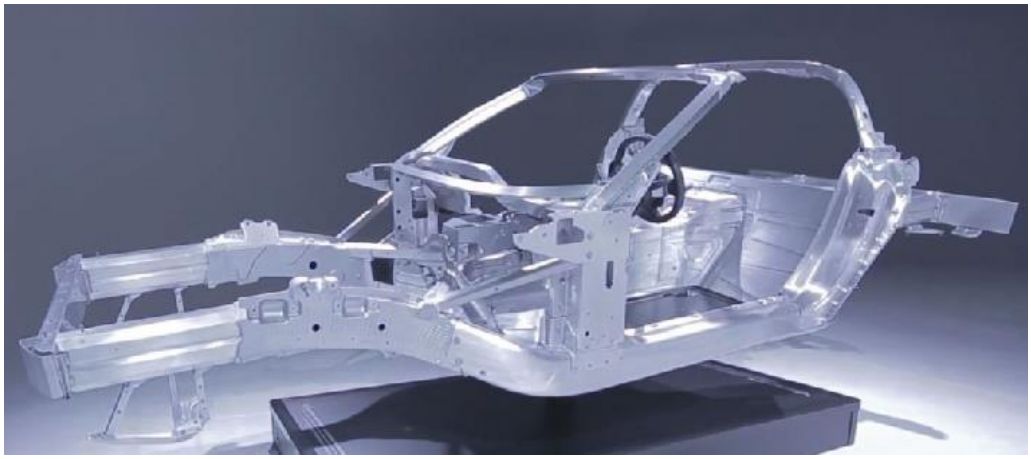
Aluminium spaceframe of the Corvette Z06

(Photo: General Motors)

Early 2013, General Motors unveiled the Chevrolet Corvette Stingray C7 with its multi-component, all-aluminium chassis, which 45 kg lighter and 57 % stiffer than the current C6 Corvette's hydroformed steel rail-based frame.

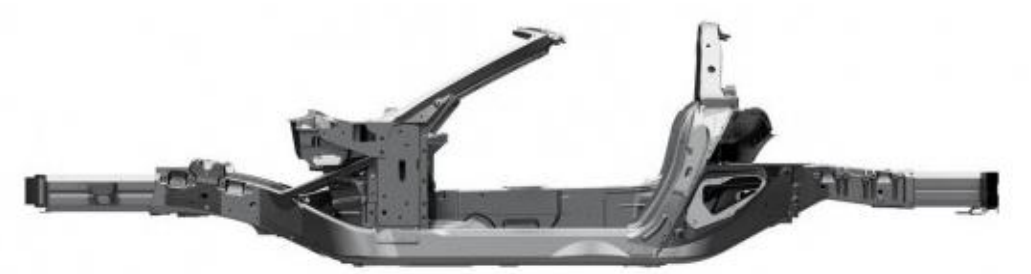
The aluminium chassis/passenger cell structure includes 10 castings, 38 extrusions, 76 stampings, and three hydroformed parts. The body structure of the C7, whether coupe or convertible, is basically an open-air design that has no roof structure to add extra support. Apart from the lighter weight, the increased stiffness and the improved crash worthiness were therefore the main factors to change from steel to aluminium.

In addition to the new aluminium structure, the C7 Corvette also uses an increased amount of carbon fibre reinforced plastics in the exterior body panels. Carbon fibre reinforced plastic panels are used selectively in the largely non-load bearing skin panels, the bonnet and the removable roof panel for the coupe, along with interior trim panels.



Aluminium spaceframe of the Corvette Stingray C7
(Photo: General Motors)

The chassis is composed of two perimeter main frame rails, an enclosed box beam-like "tunnel" structure, and a cockpit assembly. Whereas the previous C6 Corvette featured hydroformed steel-tube main frame rails with a constant 2 mm wall thickness, the C7's chassis employs rails composed of five customized aluminium segments with thicknesses ranging from 2 to 11 mm.
The Corvette's chassis assembly features part interfaces that were made using various joining methods including conventional MIG welding, a patented spot-welding method developed by GM as well as screw-bolts reinforced with adhesives. Resistance spot welding of aluminium with a newly developed multi-ring electrode eliminates the need to use self-piercing rivets.



Aluminium spaceframe of the Corvette Stingray C7

(Photo: General Motors)

The aluminium extrusions in the front crush zone are made of a high strength EN AW-7xxx (AlZnMg) alloy and are designed to folds like an accordion to absorb the impact energy. The hollow cast node at the suspension-cradle interface is composed of a high-strength aluminium casting alloy (A356). Next come a hydroformed aluminium tube centre section, followed by another hollow cast A356 node and the rear crash management system made from EN AW-6xxx (AlMgSi) alloys. In the middle of the frame structure is an aluminium box beam-like assembly with a high stiffness shear wall structure that is strengthened with four thin walled, vacuum die-cast plate reinforcements.

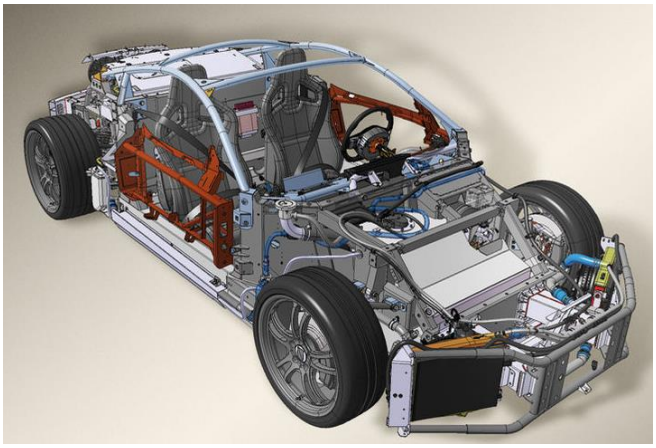
1.5.5 Mitsubishi's i car concept

The Mitsubishi i model is a super-mini car, first released in 2006. It is the first four-door automobile since the 1960's with the engine behind the passengers, in an attempt to improve safety and interior space without enlarging the overall exterior. A lightweight aluminium space frame structure and the rear-engine layout allowed the incorporation of a large front deformation zone in order to meet current safety legislation requirements without compromising interior space.

The basic framework of the original body concept consists of aluminium extrusions and aluminium die-castings, the floor and roof panels are formed from aluminium sheet stampings. Aluminium extrusions are used for the side members and cross members of the underbody and the roof side rails (which include the A pillars) and roof bows of the upper body. Vacuum-high pressure die castings are applied for the B and C pillars as well as for some connecting nodes. Aluminium stampings are used for the floor, dash panel, roof and rear quarter panels.
Some aluminium hang-on parts were later substituted by plastic panels. The Mitsubishi i-MiEV (MiEV: Mitsubishi innovative Electric Vehicle), a five-door hatchback electric car which is produced since 2009, and derivative models use a hybrid approach with a plastic roof and other hang-on parts. Aluminium is used for the rear suspension and rear body. Such a concept reduces the weight around the rear axle where the powertrain and EV system components are installed and thereby achieves an ideal 50:50 front/rear weight distribution. The aluminium spaceframe with its optimum layout of structural members, including front-side and cross members efficiently absorbs crash energy in the event of front-end or side collision. In a collision from the rear, the EV components under the back seat and rear floor serve as a barrier to ensure the integrity of the passenger compartment. Thus excellent occupant protection in collisions from any direction is ensured, even when colliding with a vehicle of different height or weight.

1.5.6 Artega GT

The Artega GT was a rear wheel driven two-seat sports car with a mid engine. The first prototype was presented in 2007. The Artega GT had an aluminium space frame and a carbon fibre reinforced body which led to a light curb weight of approximately 1,100 kg. The roof and the engine rear module were designed as a tubular space frame made of high-tensile stainless steel. On September 30, 2012 the production of the Artega GT was halted, there are no plans to resume production.



Artega GT, a sports car with an aluminium space frame complemented with stainless steel tubes and carbon fibre reinforced hang-on parts
(Source: Artega)

1.5.7 The BMW LifeDrive concept

Designing a fully electric vehicle offers the chance to completely rethink vehicle architecture. The **LifeDrive concept developed by BMW is a revolutionary body concept specially designed for alternative drivetrains. It consists of two horizontally separated, independent modules.** The Drive Module, an aluminum chassis, forms the solid basis of the vehicle. It combines the battery and drive system, plus a range of structural and basic crash components into a single lightweight, high-strength module. The key to the LifeDrive architecture concept is the integration of the battery into the vehicle structure resulting in a

low centre of gravity. The Life Module is a high-strength and extremely lightweight passenger cell made from carbon fibre reinforced plastic.

Design concept of the BMW i cars: BMW i3 (left) and BMW i8 (right)
(Source: BMW)

1.6 Mixed-material body structure designs

The described body design concepts open the possibility to realise a range of mixed constructions whereby not only the applied aluminium product forms can be varied, but also different materials or material combinations can be used. An alternative lightweight body-in-white concept to the all-aluminium design calls for applications of aluminium together with high and ultra-high strength steels, magnesium and plastics or composites, where applicable. The principle idea is to use the "optimum" material for the appropriate functions: driving performance, safety and fuel efficiency. The additional goal is to achieve an overall cost efficient light-weight design.
Specific technical solutions associated with such multi-material designs must be addressed in the areas of joining and finishing (coating) as well as in the control of different thermal expansion and protection against galvanic corrosion.
A forward-looking mixed-material concept was realised first by BMW for the 5xx (E60) series combining an aluminium front structure with a steel passenger cell. The advantage of such a design is – apart from the weight reduction – an optimized axle load distribution. With the new AUDI TT (8J), another hybrid body structure was realised where an aluminium space frame for the front section and the passenger cabin was combined with a rear section designed in high strength steels. Similar lightweight design concepts with a steel body structure and aluminium components − preferentially in the front − were further developed in various new car models.
Apart from lightweighting with aluminium, also lightweight components made from other materials (in particular fibre reinforced composites) can be applied similarly.

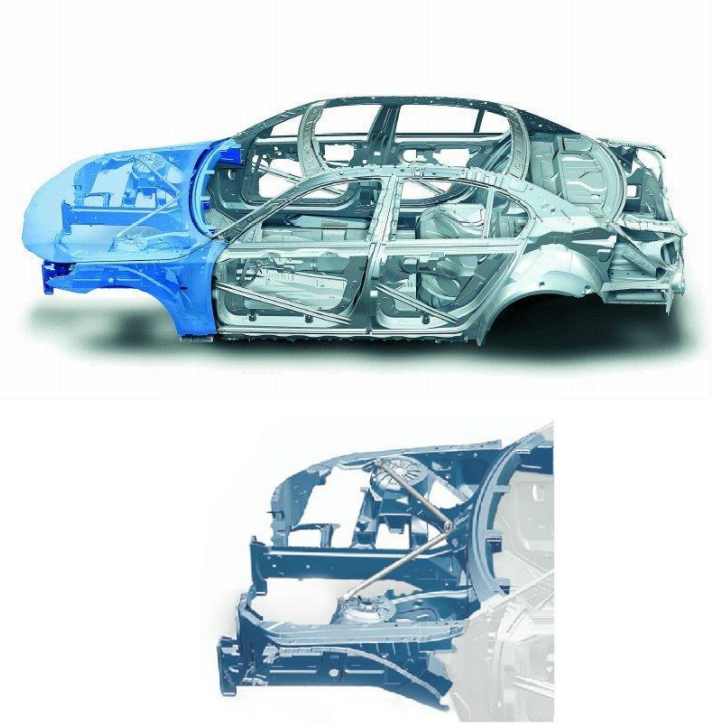
1.6.1 BMW aluminium front end

In 2003, BMW presented with the 5 and 6 series models the first car bodies with a lightweight aluminium front end. The front end consists almost entirely of aluminum while the transition to steel occurs in the front bulkhead area. The "weight-reduced aluminium front end" (GRAV) not only offers a significant weight reduction compared to the preceding model, but is also a significant factor in attaining the ideal 50/50 axle load distribution.
Consequently, the material composition of the body of the 5 series sedan was:

- 18 % aluminium alloys (including the front-end substructure, bonnet and front fenders)
- 20 % deep drawing steels
- 42 % high strength steels
- 20 % advanced high strength steels.

For the 6 series cars, which also included aluminium doors, the aluminium share increased to 26 %.

With the introduction of the new BMW 5 and 6 series cars in 2010, however, the aluminium front end was dropped and BMW returned to a complete steel body.



BMW 5 series (E60) with an aluminium front end
(Source: BMW)

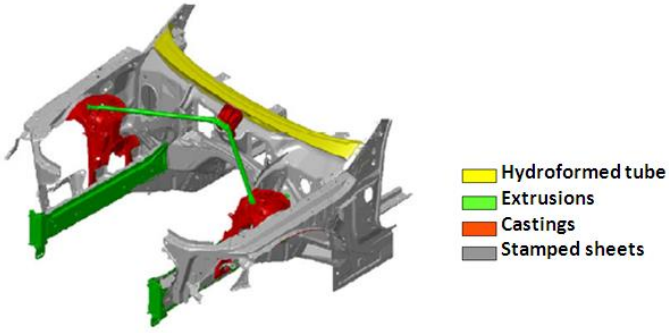
The “weight-reduced front end” includes in total 101 parts (aluminium and steel stampings, aluminium extrusions, aluminium high pressure die castings and a hydroformed aluminium tube). There are 86 aluminium and 15 steel parts. The respective weight share is:

- Aluminium 29.4 kg and
- Steel 16.4 kg.

Different aluminium alloys have been used for the fabrication of the front end:

Sheet stampings:	EN AW-5042 (AlMg3.5Mn), EN AW-5182, EN AW-6008 (T4),
Welded tube:	EN AW-5042,
Extrusions:	EN AW-6060 (T5), EN AW-6082 (T6)
Castings:	Magsimal-59™ (~ EN AC-51400DF)
Impact extrusion:	EN AW-6082.

The front longitudinal beam is an EN AW-6060 extrusion combined with an EN AW-6008 sheet panel on the outside. An extruded profile (alloy EN AW-6082) closes the front end and serves as the transition plate to the front crash management system. The suspension strut dome is a high pressure die casting. The starting product for the cross beam under the front window is a longitudinally seam welded tube (wall thickness 1.4, diameter 95 mm) made of AlMg3.5Mn which is bent and hydroformed in two steps with an intermediate anneal for improved formability. All the aluminium parts are conversion coated before assembly.

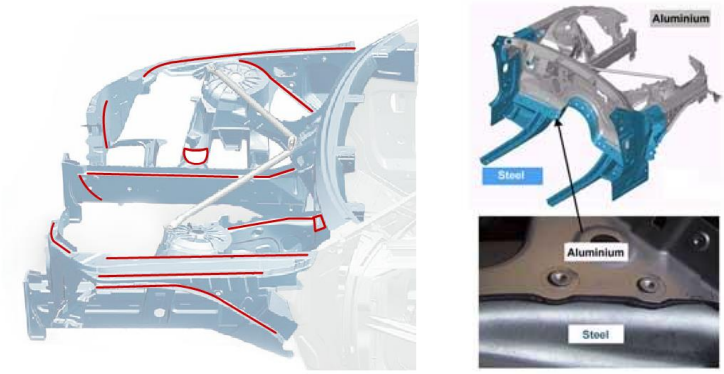


Aluminium product forms
(Source: BMW)

The following joining methods are employed in the assembly of the front end:

- Self piercing rivets: 598 rivets
- Resistance spot welding: 140 spots
- MIG welding: 3.1 m
- Laser welding: 1.7 m
- Stud welding: 48 bolts
- Adhesive joints: 15.8 m total (6.7 m aluminium / steel).

Adhesive bonding (using the epoxy adhesive Betamate 1480) is always combined with self-piercing rivets. For corrosion protection, the self-piercing rivets are ALMAC coated and the joints are PVC sealed. This approach also ensures the corrosion resistance of the aluminium/steel joints where the adhesive acts as an isolating layer. A specific challenge was the MIG welding of the thin aluminium components. For this reason, Nd-YAG laser welding (with AlMg4.5Mn filler metal) was used for a weld on the hydroformed cross beam.



Adhesive bonds in the aluminium front structure (left) and the aluminium/steel joint (right)
(Source: BMW)

Special care must be also taken with respect to electrically conducting connections, e.g. with respect to grounding. Also an aluminum body section offers reduced shielding against external electromagnetic radiation, making it necessary for separate shielding of the wiring harnesses and electronic control units. But riveted and bonded aluminium components do not always provide a guaranteed circuit to ground. This results in the need to connect individual front end components with small EMC safety weld seams.

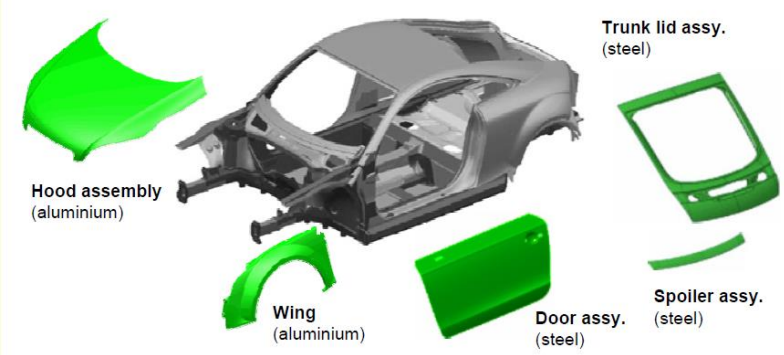
1.6.2 Audi TT

The second generation of the Audi TT (8J), which is available as a 2+2 coupe or a two-seater roadster, was revealed in 2006. It features a hybrid aluminium and steel construction. The front end, the floor and the superstructure are made of aluminium, with deep drawn steel

being used for the doors and the trunk lid. The rear section of the floor assembly, the tail panel and the bulkhead of the Roadster are made of high-strength steel. This material mix provides for an optimal distribution of axle loads and thus improved dynamic handling.

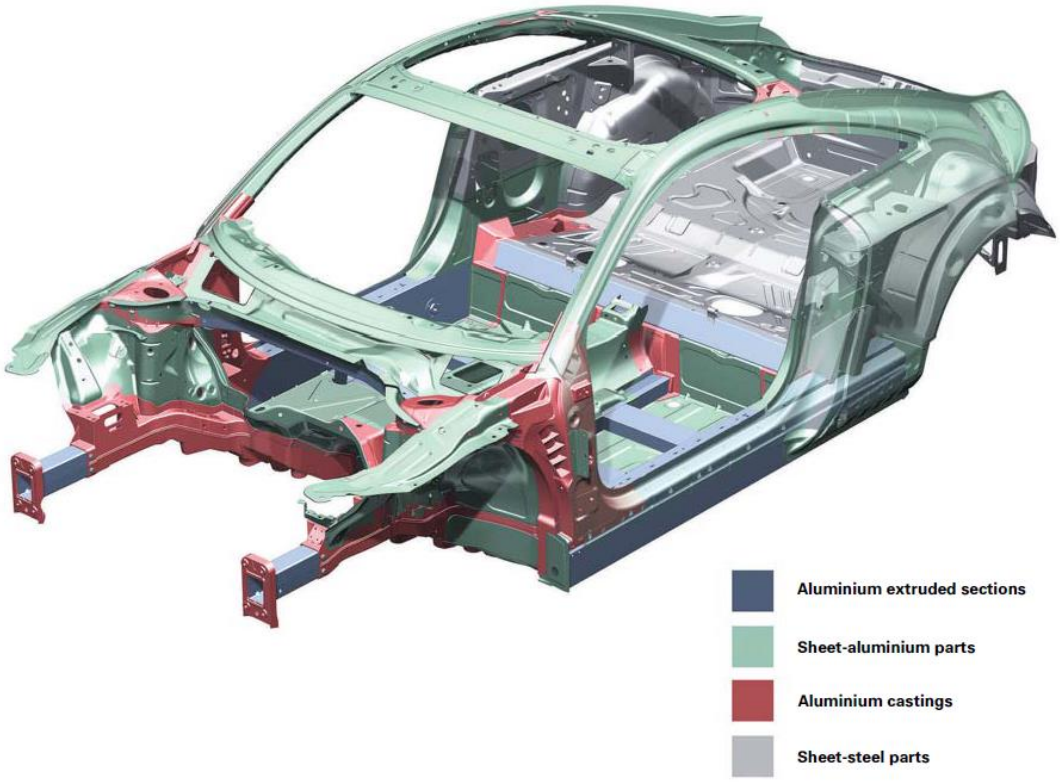
Hybrid aluminium and steel body structure of the Audi TT
(Source: Audi)

In the new Audi TT, steel sheet parts are used for the first time in the Audi Space Frame design concept together with aluminium castings, aluminium extruded sections and aluminium sheet stampings. The use of steel sheets in the rear body section improves specifically the vehicle weight distribution. Compared to the previous model with its steel body, the curb weight nevertheless decreased by 20 to 90 kg; depending on the model. At the same time, the new TT has grown in size and the static torsional rigidity was increased by 50 % in the coupe (100 % in the roadster).



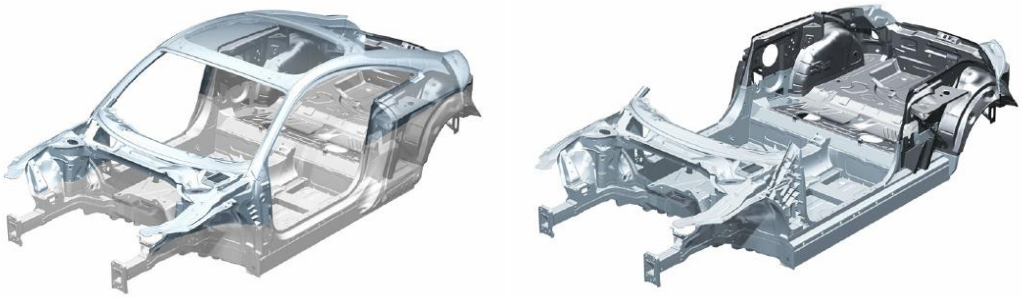
Hang-on parts of the Audi TT
(Source: Audi)

The weight of the body is 206 kg for the coupe (or 277 kg including attachments such as doors and lids) and 251 kg for the roadster. The weight advantage over a comparable all-steel body shell is approx. 100 kg. The material mix is dominated by aluminium, which accounts for 69 % of the coupe's weight and 58 % of the weight of the roadster. In the coupe, the aluminium fraction comprises 63 kg (31 %) of panels, 45 kg (22 %) of castings and 32 kg (16 %) of extruded sections.



Material product forms in the Audi TT coupe
(Source: Audi)

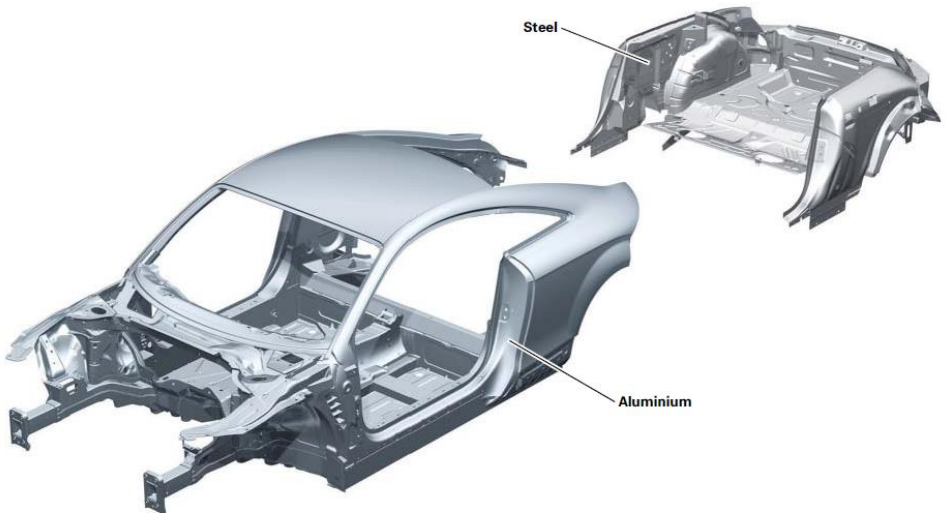
The aluminium/steel hybrid body structure also ensures a low centre of gravity. Furthermore, the crash performance of the body shell is enhanced by means of load-bearing structures at the front end, sides and rear end.



Low centre of gravity
(Source: Audi)

Special have to be taken with regard to the strength and corrosion protection of the joints between the aluminium and steel body parts. Thermal joining processes can be ruled out because it is not possible to make a joint which has the requisite structural and dynamic strength and will not result in contact corrosion.
A safe, durable joint between aluminium and steel parts is ensured by non-thermal joining using self-piercing rivets and screws in combination with adhesive bonding. The following anti-corrosion measures have been taken:

- Coating of all steel screws and fasteners such as self-piercing rivets
- Galvanising of all steel sheet parts
- Insulation of the mating materials by the applied adhesive layer
- Sealing of aluminium-steel joints either with PVC or coated with wax preservative after the cataphoretic dip coating process.



Joining the aluminium and steel body parts
(Source: Audi)

A variety of joining processes are used in the fabrication of the body of the Audi TT. A principal joining technique is self-piercing riveting (using semi-tubular rivets). It is used for joining aluminium body parts and for joining aluminium to steel body parts. Self piercing rivets with two different diameters and lengths are used. Also self-threading screws (Flow Drill Screws) are used for both aluminium/aluminium and aluminium/steel joints.
A new mechanical joining technology first used in the Audi TT is solid self-piercing riveting (Kerb-Konus rivets). In contrast to the semi-tubular rivets, solid rivets are punched through both sheets. In the Audi TT, 48 aluminium and 48 coated stainless steel solid rivets are used. Unlike steel rivets, aluminium solid rivets can be mechanically reworked. Aluminium solid rivets are used in the C post drip moulding area, while coated stainless steel rivets are used in the region of the roof frame.

Technology	Process	Quantity
Mechanical joining	Self-piercing rivets	1606 pieces
	Flow drill screwing	229 pieces
	Solid punch riveting (Kerb-Konus)	96 pieces
	Clinching	172 pieces
Thermal joining	MIG welding	21.5 m
	Laser welding	5.3 m
	Resistance spot welding	1287 spots
	MAG welding	0.8 m
	Stud welding	241 pieces
Bonding	Adhesive bonding	97.2 m

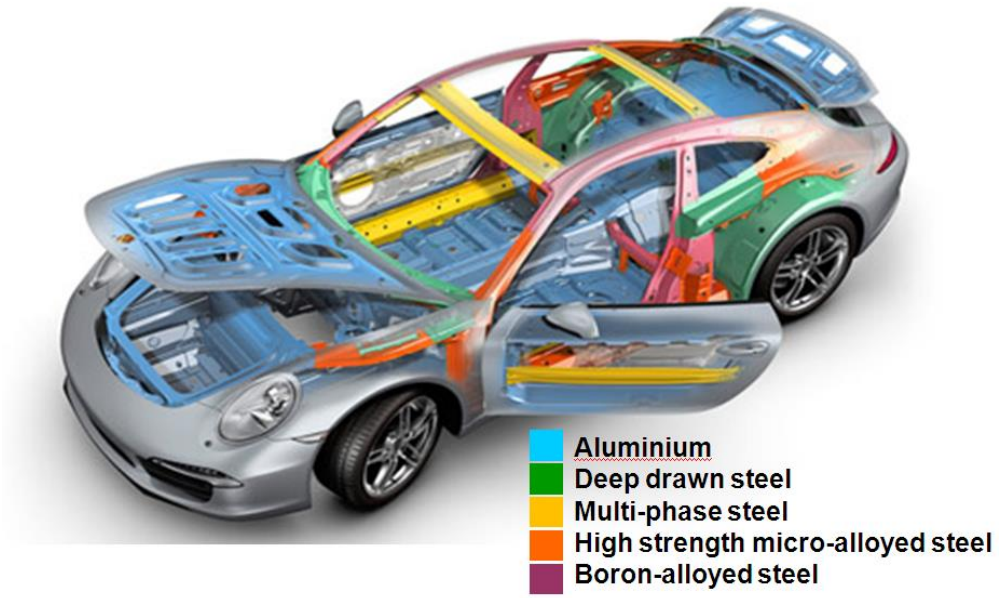
Joining technologies applied in the Audi TT
(Source: Audi)

Clinching is used on attachments such as doors and lids. Several clinched joints are also located in the area of the B pillar and rear wheel arch. In this area, aluminium sheets as well

as steel and aluminium sheets are clinched together. MIG welding is principally used for joints between aluminium castings and extruded sections, but also some sheet parts. For the assembly of steel parts, the usual techniques of resistance spot welding and, to a lesser extent, metal active gas welding (MAG welding) are applied.
Laser welding has been used for welding aluminium sheet parts onto castings or extruded parts before. But as a first in the Audi TT, also the invisible joint in the roof area is joined by laser welding. The joint between the roof frame and roof panel is reworked and surface finished automatically in the production line using a brushing process. Consistent laser welding of aluminium parts requires a perfectly clean surface of the parts to be welded. This is ensured either by washing the components followed by chemical pickling or by the application of a new laser cleaning process where a controlled laser beam running ahead of the welding beam removes all residues from the surface.
In certain areas, adhesive bonding is used supplementary to clinched and punch riveted joints, flow drill screw connections as well as resistance spot welds in order to improve joint strength. Adhesive bonding is also used for strengthening of seam joints, e.g. in the rear wheel arch. In other areas of the body, adhesive beads are used for sealing and insulation between aluminium and steel sheets, as well as for noise reduction.
The application of all these measures allowed an increase of the degree of automation in the body shop from 30 % for the preceding TT model to approx. 98 % for the new Audi TT.

1.6.3 Porsche's aluminium-steel hybrid body shell

With the new 911 Carrera coupe and cabriolet (type 991), Porsche introduced in 2012 a completely redesigned lightweight aluminium-steel body construction. The underlying idea of this design is the use of the right material in the right place. The extensive use of aluminium to reduce the vehicle's weight is balanced with elements of steel of varying degrees of strength for a more rigid body and optimum occupant protection. Parts that are especially important for passive safety, such as the inner roof frame and the B pillar, have been made in ultra high-strength, boron-alloyed steels. A continuous side impact support strut made of square ultra high strength steel is fitted between the B pillars. Also the side panels have been reinforced with high-strength components, like the door sills and door reinforcement beams. The new modular roof design also provides advantages in terms of weight. For the series model without a sliding roof, the steel outer skin of the roof has been replaced with aluminium.

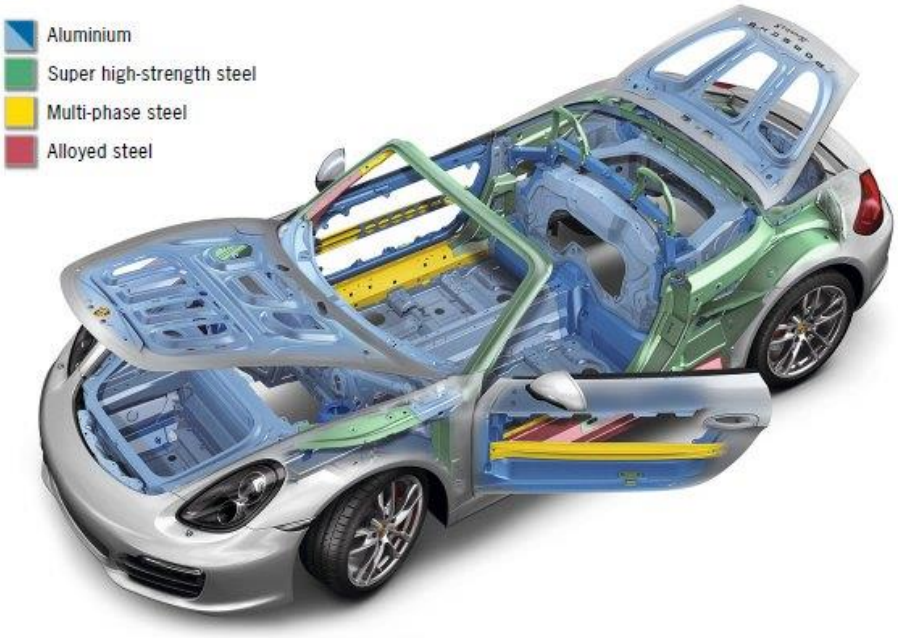


Material use in the Porsche 911 Carrera
(Source: Porsche)

The new aluminium-intensive body construction leads to a weight reduction of the new model of up to 45 kg compared to previous generations. Up to 45 kg less total weight than the

previous generation, however, means a total weight reduction of 98 kg in the basic vehicle design. Increased safety requirements, a longer wheelbase, fuel consumption reduction measures and a more powerful engine first led to a weight increase of around 58 kg in comparison to the previous models. In addition, the reinforced aluminium-steel body shows an increase in dynamic torsional stiffness of up to 25 % compared with that of the previous model
Aluminium is used for about 45 % of the body shell, including the floor, roof, doors, engine compartment lid and all structural and exterior sheet panels forward of the windshield. Apart from the passenger cell, steel is limited mainly to the piece that forms the rear quarter-panels and door frames, a complex single part that requires seven separate stamping steps. Magnesium is used for cockpit and centre console support beam and, in the cabriolet models, the bonnet shell elements.

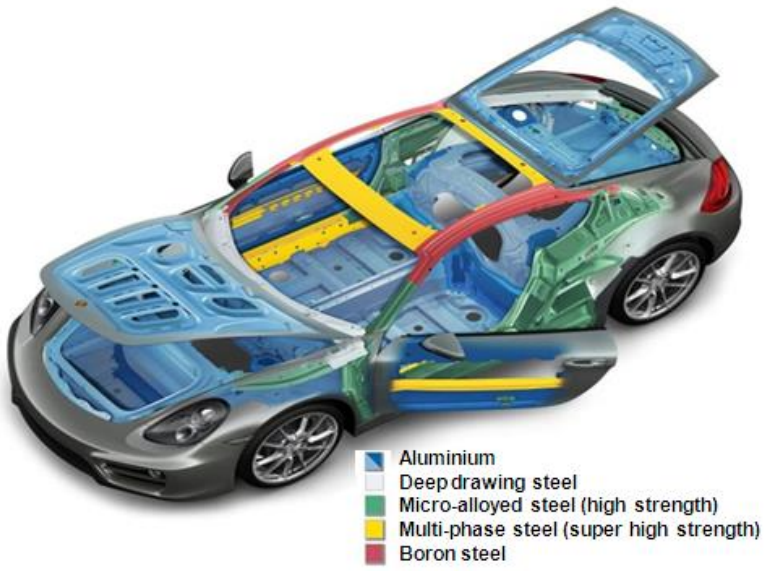
With a weight of 1,470 kg, the cabriolet is 60 kg lighter than the predecessor. Another interesting fact is the weight difference between the cabriolet and the coupe. The cabriolet is only 70 kg heavier than the coupe, compared with the usual weight difference of around 100 kg. The cabriolet has a folding fabric roof with a predominantly cast magnesium frame; aluminium is only used for a few hood frame links.
The chassis of the third generation Boxster (981), presented in 2012, is also an aluminium-steel hybrid construction, similar to that of the 911. Aluminium comprises of 46 % of the whole body-in-white. Aluminium parts include outer panels like the front bonnet, engine lid and doors as well as structural components like the floor pan, bulkheads, door frames, and the frame for mounting rollover hoops and nearly the whole front and rear structures. High-strength steel and boron steel are used mainly around the survival cell to provide the necessary crash protection with minimum space requirement. The dash support and the frames of soft roof are made of magnesium. Overall, torsional rigidity has been increased by 40 % from the preceding model, while kerb weight has been cut by 25 to 35 kg.



Material forms in the Porsche Boxter (981)
(Source: Porsche)

Both vehicles use a mix of materials, but aluminium is the main structural material. For convertibles aluminium or fibre reinforced plastics are a good choice of body material since the only connection between the front and rear sections of the car are the central tunnel and sills. Thus materials with inherently better stiffness for a given weight offset the need to use more material than in a body shell with a fixed roof.
Also the body of the new Cayman is an entirely new development based on the mixed aluminium-steel body-in-white of the Boxster. Around 44% of the new Cayman body-in-white consists of aluminium, including the front body, floor and rear body, the doors and the front

and rear boot-lids, reducing the structure's weight by 47kg. At the same time, the car's static torsional rigidity has been boosted by 40 %.

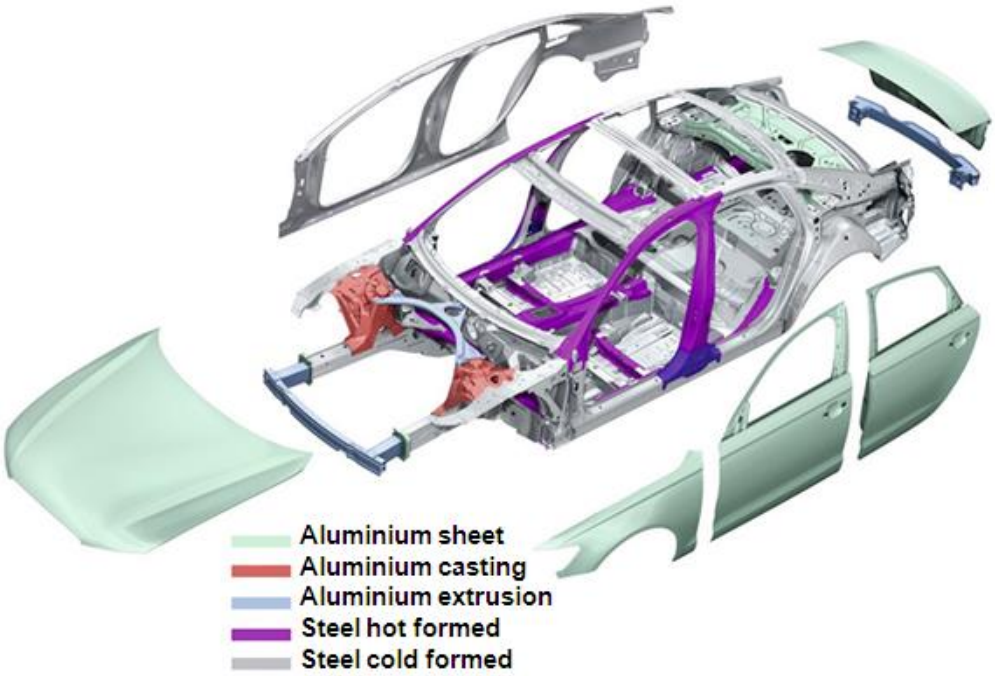


Material forms in the Porsche Cayman
(Source: Porsche)

The new vehicle benefits from the use of die-cast aluminium, sheet aluminium, magnesium and high-strength steels and now weighs 1,320 kg, compared to the previous generation's 1,330 kg, Some of the weight reduction has been offset by a larger glass surface area and larger wheels.

1.6.4 Hybrid steel-aluminium body of the Audi A6 (2011) and A7

The bodies of the new Audi A6 (C7) and the A7 Sportback show a hybrid steel-aluminum construction which weighs roughly 15 % less than a comparable all-steel body. They are made up of more than 20 % aluminium, making them roughly 30 kg lighter than that of the previous A6 model.



Hybrid steel-aluminium body as used for the Audi A6 (C7) and A7 Sportback (Source: Audi)

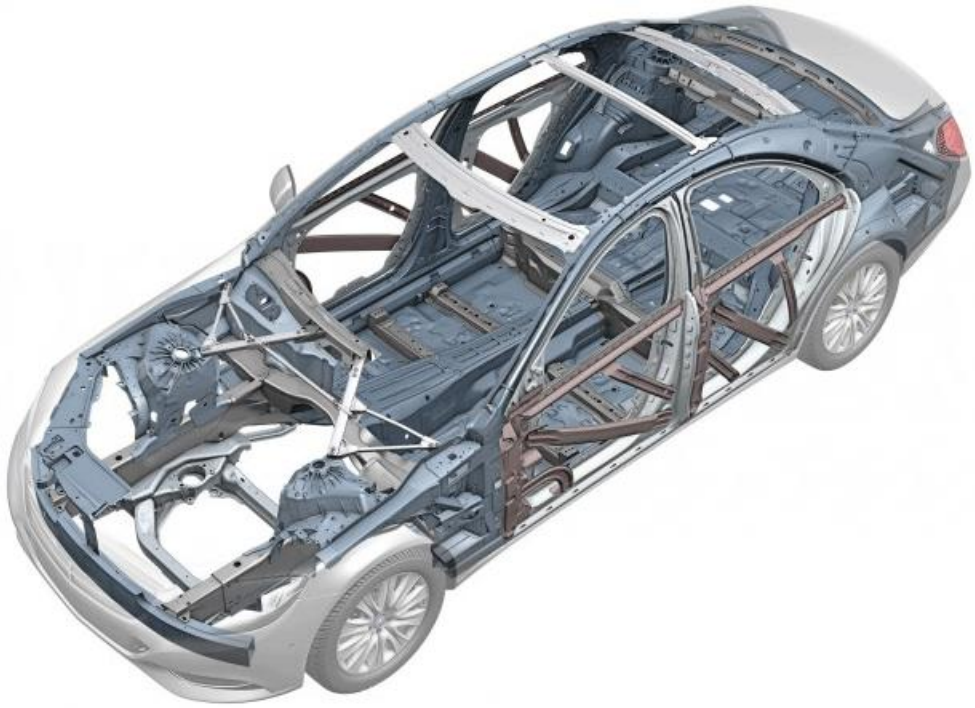
The hybrid concept provides the basis for systematic lightweight construction. The aluminium components are largely concentrated in the front end, i.e. specifically improving the axle load distribution. The crossbar in the engine compartment and the cross-members behind the front and rear bumpers are extruded aluminium sections. The front strut domes are aluminium castings. Also the control arms, pivot bearings and wheel carriers include aluminium components to reduce weight. The integral subframe behind the instrument panel, the rear shelf, the bulkhead to the trunk, the cross-member in the trunk, the front fenders, the doors, the bonnet and the trunk lid are made of aluminium panels.
The passenger compartment of both the A6 and the A7 Sportback includes components made of hot-shaped steel. They can be found in the transition from the front section of the car to the passenger cell, in the A-pillars and the roof arch, as reinforcements for the centre tunnel and the side sills, at the transition of the side sills to the rear section of the car, as cross-bracings in the floor panel and as B-pillars. In many zones, such as the bulkhead cross-connection, Audi uses tailored blanks. In some areas, the steel components in the body already follow the ASF (Audi Space Frame) principle. Thus the A6 and the A7 Sportback represent a gradual transition from the monocoque design to a new multi-material space frame.

Hybrid Steel-aluminium body structure of the Audi A7 Sportback

(Source: Audi)

1.6.5 Aluminium hybrid bodyshell of the Mercedes-Benz S class (W222)

Mercedes-Benz describes the body of the 2013 S class model (W222) as a third-generation aluminium hybrid bodyshell. The body consists of 50% aluminium in combination with high- and ultra-high strength steels. A lightweight design concept by material and geometrical optimisation coupled with a highly complex joining technology (specifically the application of additional mechanical joining technologies) allows the new S class model to further raise the bar in the demanding luxury saloon segment – without adding weight. The lightweight index, the torsional stiffness in relation to weight and vehicle size, has been improved by 50% compared to the predecessor model. A further design goal was a better NVH performance than the already very good preceding model.

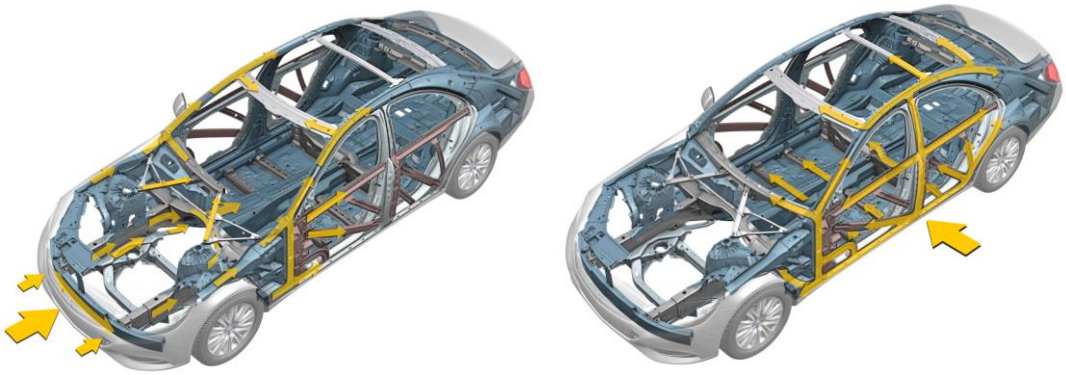


Aluminium hybrid bodyshell of the Mercedes-Benz S class (W222)
(Source: Daimler)

The entire outer skin of the S class model, including the roof and the front section of the body, consists of aluminium. In the case of detachable body parts such as the wings, bonnet and boot lid, the use of aluminium adopted for the previous model series was continued. A new development is, however, the lightweight aluminium front section which also greatly enhances crash and NVH performance. Cast aluminium and extruded aluminium sections are used in addition to sheet aluminium. Die-cast aluminium was chosen for the shock absorber strut bracket because of its good integration properties. In this way, it was possible to connect the front module without additional holders. In order to improve the safety system as a whole, a cross-functional load path was conceived. Additional support is provided by the aluminium struts running in X-direction from the shock absorber strut bracket to the cowl. Supplemented by a multi-piece framework, these struts also help to suppress the Y-movement of the side members. This design allowed the incorporation of a new load path into the limited package installation space in the front section. The forces are applied to the bodyshell structure in the three-piece cowl, which has been configured as a cast aluminium component in the centre section. The casting allows a functionally perfect connection with distinct advantages in terms of weight and installation space. The firewall area is a sheet steel design which also allowed the integration of the complex hybrid joint between the aluminium front section and the steel cell.

In addition to the front section, the integral carriers are also made of aluminium. As well as acting as a component carrier for numerous components (i.e. the complete cooling module in addition to the engine, steering, torsion bar and front axle), the integral carrier is a central component of the front-end structure when it comes to performing crash and NVH functions. The integral carrier's side members also form the third crash load path in the front section. In order to meet these multiple requirements, a complex aluminium mix comprising die castings/permanent mould castings, extruded sections and sheet metal parts was also required here.

The side members have been designed as combined aluminium extruded sections/castings to optimise crash performance, rigidity and component integration. The protrusions of the extruded aluminium sections of the side members required for package reasons have been designed to also have a positive effect on folding behaviour in the event of a crash. The side members are connected to the steel passenger cell by means of cast aluminium components that allow a very rigid connection and integration of the integral carrier connection.
The aluminium roof is another key area for lightweight design as reducing weight here has a positive effect on the vehicle's centre of gravity and on NVH characteristics. A major challenge here was integrating the roof into a steel structure. This was achieved by implementing an efficient and simple assembly solution in the bodyshop, which involves the roof being fixed to the bodyshell structure using shackles with defined spacing for the purpose of production in the factory.



Crash load paths in the Mercedes-Benz S class (W222) body structure (Source: Daimler)

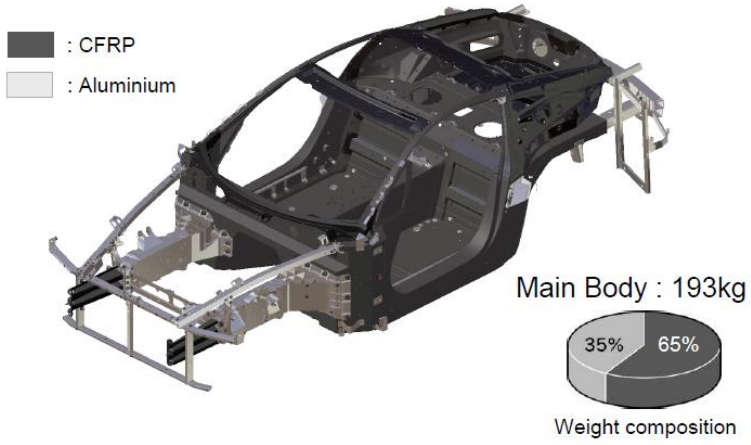
The safety passenger cell is made using an extremely high percentage of high-strength steel, including roll-formed boron steel in critical load path areas. The rear panel and cockpit cross-member are designed as hybrid metal/plastic constructions.In addition to this, structural

foams sections are used in the A/B/C-pillars to increase bodyshell rigidity and ensure high NVH performance.
In order to reduce the loads exerted on a pedestrian if their head hits the bonnet of the vehicle, the deformation space between the bonnet and the components beneath it has been optimised. This was achieved in part by appropriate positioning of components such as control units or fluid reservoirs in the engine compartment. Furthermore, the S class model features an active aluminium bonnet with a homogenously reinforced inside face. In the event of a collision with a pedestrian, sophisticated sensors combined with intelligent algorithms trigger pyrotechnic actuators in the area of the bonnet hinges which raise the bonnet by around 80 mm.

1.6.6 Mixed aluminium/CFC designs

Carbon fibre reinforced plastics (CFRP) can be used to build the chassis or the frame of a vehicle instead of the usual choice of metals. However, a chassis can also be only partly made of carbon fibre composites. In this case, the other part is usually aluminium and both parts are bolted together.
Several supercars use a carbon fibre tub around the passenger compartment with the rest of the chassis extending forward and rearward of the tub made of aluminium.

As an example, the Lexus LFA utilises a hybrid carbon/alloy chassis, with its carbon fibre central structure bonded to aluminium subframes at the front and rear.



CFRP cabin and aluminium frame of the Lexus LFA (2010)
(Source: Lexus)

Another example is the Mercedes-Benz SLR McLaren (199), a super sports car which was produced by McLaren between 2004 and 2009. A sand cast aluminium engine carrier separates the front impact zones from the CFRP passenger compartment.

Body structure of the Mercedes-Benz SLR McLaren
(Source: Daimler)

Most interesting is also the Audi Crosslane concept which was presented at the Paris auto show in 2012 with its multi-material space frame. Extruded aluminium profiles form a stiff, closed structure around the passenger compartment. Aluminium sections underneath the bonnet connect the aluminium frame around the grille, which has also a structural function, with the safety cell. The front and rear crash management systems are made of carbon fibre reinforced composites, other carbon fibre reinforced composites within the passenger compartment such as the interior sill beams, firewall, tunnel and floor cross beams are also part of the supporting structure. Planar glass fibre reinforced plastic panels complete the car body structure.

Audi Crosslane 2+2 coupe concept
(Source: Audi)