

Aluminium in Innovative Light-Weight Car Design*

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The main Aluminium applications as state-of-the-art in European cars are presented. The main established Aluminium alloys and their application in automotive parts are presented together with recent developments. Also new studies and innovative multi-material concepts are discussed where Aluminium light-weight solutions are compared with that of other materials, like new steels, magnesium, plastics and composites. In the “SLC” (Super-Light-Car) project these new concepts were tested in a multi-material body-in-white prototype for a VW Golf V car, reaching a 34% weight reduction within a cost increment of 7,8 €/kg saved, with suitable technologies for high volume assembly cycles. In the final SLC concept Aluminium is the material of choice, proving its leading role in innovative light-weighting of cars. Aluminium achieves weight savings of parts up to 50% while maintaining safety and performance in a cost efficient way, competing efficiently with other light-weight materials. [doi:10.2320/matertrans.L-MZ201132]

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1. Introduction

Innovative car concepts are needed to solve the global conflict of public and private mobility and environmental efficiency and critical CO₂ emission. In spite of some customer demand on high performance, size, extra comfort that boost the weight spiral, car companies try to respond by new (e.g. electric “E”-) car concepts, including a consequent light-weight design to the growing public awareness on fuel consumption and stringent legislative regulations on CO₂ emissions in Europe. 100 kg saved on the mass of a car can save about 9 grams of CO₂ per kilometer, so a reduction of vehicle mass is mandatory, as the most effective measures to reduce CO₂ emission and at the same time maintain performance, driving quality and—most of all—safety.

By light-weighting with Aluminium, weight savings of parts up to 50% can be achieved. Aluminium solutions are already well established in power-train, chassis, car body, hang-on parts, bumpers and interiors, but preferentially in high class cars (e.g. AUDI A8, Fig. 4(a)). Full aluminium bodies allow weight saving of 70 to 140 kg (i.e. 30–40%) depending on the size of the car.¹⁾ And now light-weighting becomes more attractive also for smaller and for mass produced cars, since car manufacturers have learned the specific aspects of Aluminium application and handling.²⁾ In a growing competition, however, also other light-weight materials like new high-strength steel grades, magnesium (castings and sheet) and (fiber-reinforced- or thermo-) plastics are being tested and new innovative multi-material concepts are developed, with different focus by the leading OEMs.^{3,4)}

The EU funded “Super-Light-Car” SLC project had analyzed all these materials, their performance, fabrication and joining costs in a multi-material body-in-white concept for a running VW Golf V car, including detailed life-cycle-analysis “LCA” of all materials involved. The final concept and prototype build reached a 34% weight reduction without compromising performance and safety^{3–5)} and a cost increment of 7,8 €/per kg saved. Furthermore suitable technologies

for high volume assembly cycles (<1 min) were evaluated and verified. In many parts of the SLC concepts and prototype Aluminium was the material choice. This also held for the end-of-life cycle perspective investigated for all the materials employed. Also here Aluminium wins with its high recycling rates in cars and the fact that only 5% of the original energy consumption is required.

2. Aluminium Application in European Cars

In Europe a highly innovative automotive industry has introduced various light-weighting car concepts and parts (e.g. Fig. 1) based on existing, newly developed or improved Aluminium alloys.^{5–7)} The total amount of aluminium used in new European cars rose from 62 kg in 1990 to 132 kg in 2005 (Fig. 2⁸⁾). With a slight retardation due to the economic crisis it is predicted to continuously grow further in the same rate.

An optimized Aluminium oriented car design has been established in many parts and applications (cf. Fig. 1) and analyzed systematically for the main European cars:¹⁾

- (1) 69 kg in POWTRAIN in engine block & cylinder head, transmission housings, fuel system, liquid lines and radiators.
- (2) 37 kg in CHASSIS & SUSPENSION in cradle, axle, wheels, suspension arms and steering systems.
- (3) 26 kg in CAR BODY (Body-In-White “BiW”, hoods/bonnets, doors, front structure, wings, crash elements and bumpers and various interiors.

The heaviest part of a conventional (steel) car is the Body in White (BIW)—seen as one component—with a share of up to 30% of the complete car’s weight, depending mainly on the options installed, engine size, and integrated safety and comfort features. It has the highest weight saving potential through increasing the Aluminium content and in Europe is growing fastest in this direction.

3. State-of-the-Art for the Body in White (BIW)

Figure 3(a) shows the *Aston Martin Vanquish*, Model Year 2001 with a volume of 350 cars per year. It is an “extrusion intensive” state-of-the-art BIW and weighs

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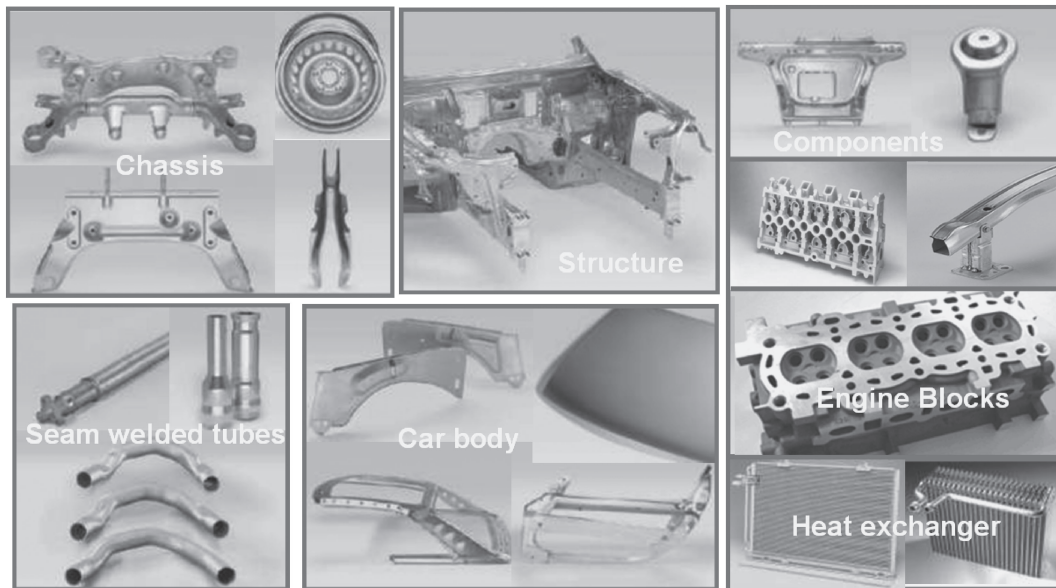


Fig. 1 Aluminium products for advanced automotive applications.

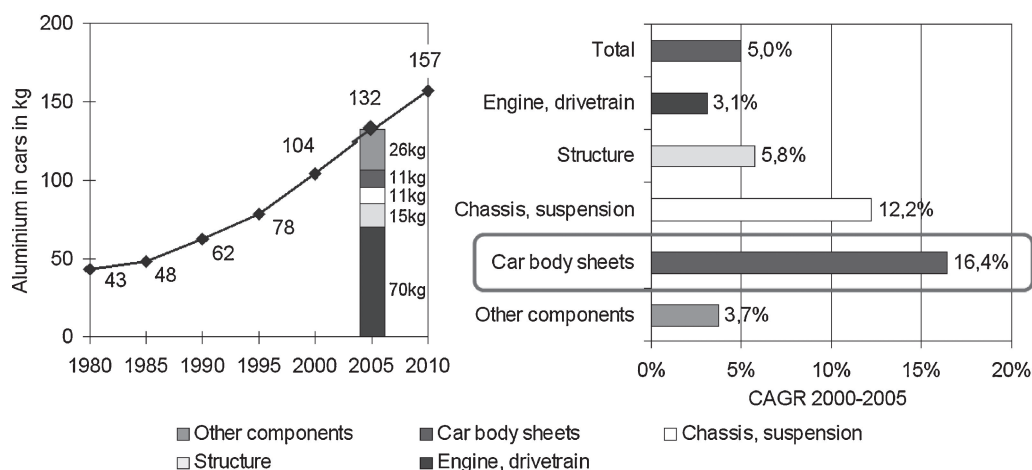
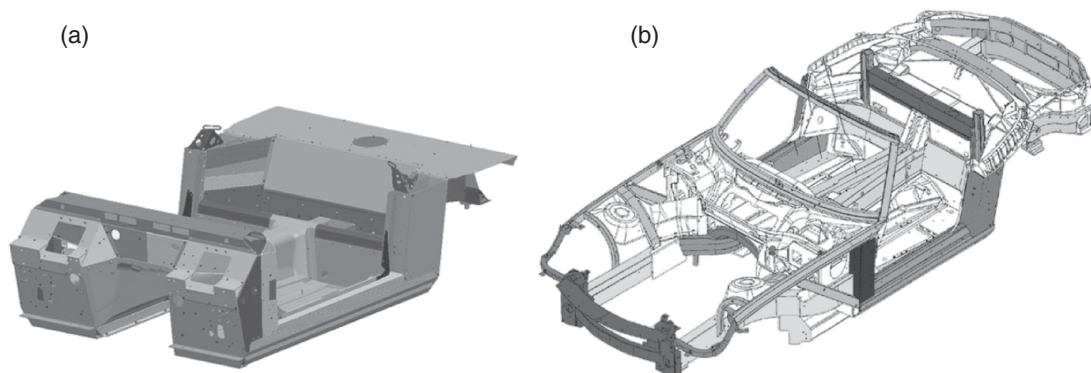
Fig. 2 Penetration of Aluminium in European Cars (Strongest growth of Aluminium in car body sheet application!).⁵⁾

Fig. 3 State-of-the-art Body in White "Extrusion intensive design".

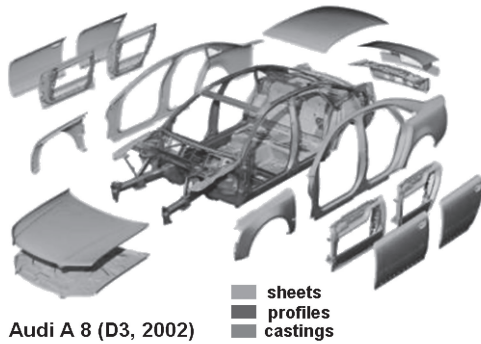
145 kg (excluding closures and outer skin), consisting of 40 extrusions (100 kg) and 40 sheet parts (45 kg) with rivets and adhesive bonding as main joining methods.

The **BMW Z8 Roadster** (Fig. 3(b)) has a volume of 2.500 cars per year with a BIW mass of 300 kg with 86 straight and

24 bent extrusions. As joining MIG welding and rivets (1.000 pcs) are applied.

For the **Audi A 8 (D3)** (e.g. Fig. 4(a): Model Year 2002) the "Space Frame concept" ("ASF") was developed with BIW mass of 277 kg that consists of 59 extrusions with 61 kg, 31

(a) Space Frame



Audi A 8 (D3, 2002)

(b) Stamped Sheet Monocoque



Jaguar XJ 2002

Fig. 4 “Aluminium Space-Frame vs. Stamped Sheet” Concepts.

castings with 39 kg and 170 sheet parts with 177 kg. Rivets (2400), MIG, Laser, Laser-Hybrid welds, Roll-folding, adhesive bonding are the main joining methods applied. With a scheduled volume of 25.000 cars/year the ASF is now an established concept with almost 600.000 units built so far. (Audi recently lodged the new A8!). According to AUDI, it now weighs about 245 kg which is significantly (40%) lighter than a comparable light-weight steel version. The new AUDI R8 BiW only weighs 212 kg.

The *Jaguar XJ Model Year 2002* (Fig. 4(b)) still uses the classical “Stamped Sheet Monocoque”, scheduled for large volume productions of 30.000 cars/year. It has an Aluminium BIW mass of 295 kg, consisting of 22 extrusions with 21 kg, 15 castings with 15 kg and 273 sheets with 259 kg weight. Joining methods used are mainly adhesive, rivets (3.000 pcs), clinches and MIG welding.

As an alternative to the all-Aluminium designs there is a new concept of “*Multi-material designs*” with the. It uses the “best” material for the appropriate functions and consists of applications of Aluminium together with (ultra-) high strength steels, magnesium and plastics or composites, where applicable, also in high volume cars, achieving an overall cost efficient light-weight design. As state-of-the-art in this area the BMW 5-E60 uses 20% as deep drawing steels, 42% as higher strength steels, 20% as highest strength steels and 18% Aluminum alloys. The front-end substructure consists of 16,4 kg steel and 29,4 kg in 86 Aluminum parts (as stamped sheet, extrusions, high-pressure die castings, and hydro-formed tubes).

4. Aluminium Alloys Used in Automobiles

For most automotive parts made from aluminium two alloys are used:

i) Non-heat-treatable or work-hardening AlMg(Mn) alloys (5000 series alloys) that are solid solution- (and evtl. strain-) hardened, showing a good combination of strength and formability.

ii) The heat-treatable AlMgSi alloys (6000 series alloys) that obtain their required strength through the heat treatment cycle, e.g. for sheets when the car body undergoes in the paint baking process.

The latter are also the main alloy for extrusions, since they achieve high extrusion speed and surface quality, with

optimized age hardening characteristics, when cooled from the extrusion process. In some cases also heat-treatable AlZnMg alloys (7000 series alloys) are used for special high strength applications, but in most cases the robust and easy handable (and weldable) 6000 alloys prevail. In recent development certain properties are especially designed by sophisticated alloy and process combinations, as discussed below for the specific applications. Also new material combinations by roll cladding⁹⁾ or the new “Fusion” casting technology¹⁰⁾ with a higher strength core and a corrosion resistant surface (e.g. clad AlMg1) are recent innovative developments used in European cars (applied e.g. in the new BMW 7 series). They combine different properties in an efficient symbiosis (e.g. inner strength with superior surface appearance, corrosion resistance or formability). These combinations also show an increased formability and replace some monolithic alloy solutions.

Also new AA6000 alloys have been developed that show designed properties of improved bake hardening response “fast bake hardening” or improved forming characteristics “high formability” for a specific application or process. High formability 6000 sheet show elongation to fracture values of 30% or more in all directions in the T4 condition, combined with a typical bake hardening response, resulting in in-service strengths similar to conventional AA6016 sheet alloys.⁹⁾ The forming constraints of today’s 6000 automotive sheet alloys for hang-on parts are exemplified by the common use of 5000 series alloys for non visible (inner) parts with a high demand on formability, like door inner panels, in combination with a 6000 (AA6016 and AA6014) alloy for the visible (outer) part.

5. Aluminium in Chassis Applications

Weight saving in the chassis can also achieve 40% in comparison to conventional steel chassis. It has the additional benefit of improving the driving dynamics, ride comfort, and safety due to the reduction of the unsprung mass. Figure 5 shows some examples of chassis applications with non-heat treatable 5000 series Aluminium alloys. 5000 alloys like AA 5049 (AlMg2Mn0.8) and AA5454 (AlMg3Mn) are used comprising good formability (including interannealing capability) and weldability, high strength after forming, and outstanding corrosion resistance, also in the uncoated



Fig. 5 Example of chassis components made of aluminium.

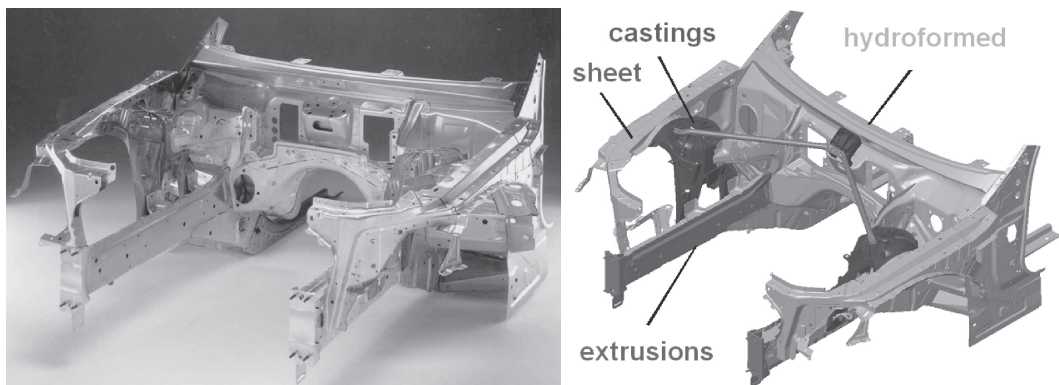


Fig. 6 Weight-reduced aluminium front end of BMW 5-series "GRAV" (Source: BMW).

condition. For certain parts, however, that experience long-term thermal loads (as e.g. in the vicinity of the car's engine or exhaust system) the Mg content is limited to ≈ 3 mass% to avoid the potential danger of intergranular corrosion (IGC), due to (slow) possible microstructural changes by Mg precipitation along grain boundaries (known as sensitization) at elevated temperatures ($>70^{\circ}\text{C}$) with an exposure to aggressive environment. Special 5000 series alloys (e.g. alloy AA5042-AlMg3.5Mn) have been developed where sensitization is avoided by special alloy additions and processing steps, yielding a favourable combination of static strength and IGC resistance, now being applied in series production for chassis applications.

6. Aluminium in the Vehicle Structure

In this recent 5-series cars BMW achieved a weight of 47.6 kg for their aluminium intensive front-end structure "GRAV" (Fig. 6) made of extrusions, castings and sheet, with a 30% weight saving compared to the steel. This innovative construction fulfils all requirements regarding strength (incl. fatigue under vibratory stresses), stiffness, formability (crash behaviour), reliable process ability as well as good corrosion resistance. Furthermore, the new front-end weight balance significantly enhances driving behaviour,

furthermore crash behaviour, sufficient, could also be fulfilled. New 5000 series sheet alloys with Mg contents over 5% represent a direction of alloy development with great potential for use in car body structures. They offer substantially higher strength while, at the same time, showing improved formability.

7. Aluminium for Doors, Closures and Outer Panels

For these components a defect-free surface finish is important, in addition to formability, buckling strength, proof strength, and a suitable behaviour with regard to thermal loads from the manufacture (e.g. age-hardening or softening behaviour during paint baking) or during service life of the vehicle. For car body applications (outer panels and interior components), heat-treatable alloys of the 6000 series as well as non-heat-treatable 5000 series aluminium wrought alloys in typical sheet thicknesses of between 0.8 and 1.25 mm are used.

Due to the strong solution hardening effect of Mg both strength and formability are increasing with Mg content. Thus, for applications in the structure and for painted components where IGC has no effect high Mg 5000 series alloys are common, as e.g. alloy AA5182 (AlMg4.5Mn0.4) and moreover 5000 series alloys with high Mg contents

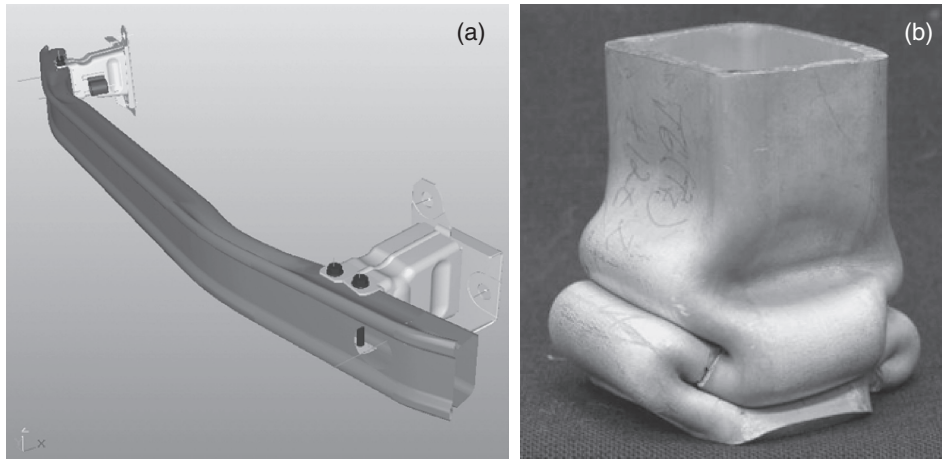


Fig. 7 Aluminium extrusions in bumper beams and crash boxes (a) Buckling of crushed extrusion (b).

(>5 mass%) have been developed.¹¹⁾ BiW exterior panels (Fig. 1) are preferentially produced from heat treatable Al-Mg-Si EN-AW 6000 alloys due to their bake hardening behaviour and optimum surface appearance.

This is also valid for hang-on-parts. Here Aluminium 6000 series alloy sheets are preferred due to their favourable property mix of excellent surface quality after forming, compatibility with the OEM process (i.e. strength increase in the paint bake cycle, compatibility with joining operations like adhesive bonding) and in-service corrosion resistance. New 6000 series alloys with higher formability and similar paint bake hardening give more freedom of design and offer the potential to produce more complex parts in an efficient and economic way.

8. Extrusions

Another special field of Aluminium solutions and applications is the well established technology of Aluminium extrusions. Here quite complex shapes of profiles can be achieved allowing innovative light weight design with integrated functions. In Europe complete new and flexible car concepts (e.g. the aluminum space frame, Fig. 4(a)) and complex sub-structures (e.g. in chassis parts, bumpers, crash elements, air bags, etc.) have been developed using extrusions. Their high potential for complex design and functional integration is most suitable for cost-effective mass production. Commonly, medium strength AA6000 and high strength AA7000 age hardening alloys are used, since the required quenching occurs during the extrusion process. Formability and final strength is controlled by heating for age hardening. Extrusions are applied for bumper beams and crash elements/boxes (Fig. 7). The main drivers in new developments are extrudability, tolerances and strength, particularly for strength relevant applications in the cars. New alloys are being developed that show higher strength. Simultaneously, it is easier to extrude and even more complex shapes can be produced, cf. the drawing of the thinwalled shapes. Today, extrusions are used extensively when tight tolerances can manually be compensated. The ductility in a T7 condition is good and the alloy should have the potential of meeting the toughest requirements for automotive applications. Axial

crushing is a relevant test for observing the buckling behaviour. Figure 7(b) shows a successful trial.

9. Castings

The highest volume of Aluminium components in cars are castings, such as engine blocks, cylinder heads, wheels and special chassis parts. The substitution of cast iron engine blocks continues, even for diesel engines, which in Europe have gained a substantial increase in market share in Europe. However, due to the high requirements on strength and durability, cast iron is still often being used. Significant progress in Aluminium alloy development (Al-Si-Cu-Mg-Fe-type) and better process control and casting methods improved material properties and functional integration that enables Aluminium to meet the specific high requirements.

Aluminium castings are also gaining acceptance in the construction of space frames, axle parts and structural components. Complex parts are produced by high integrity casting methods that ensure optimal mechanical properties and allow enhanced functional integration.⁵⁾ For high pressure die cast “HPDC” new AlSiMgMn alloys have been developed with enhanced strength and ductility combination. A typical BIW casting (A-pillar) is shown in Fig. 8(a), integrating functions connecting the B-pillar instrument panel and the front-end structure with ribs for stiffness purposes.

Crash-and strength relevant alloys (e.g. AlSi9MgMn) tailored for chassis- and BIW applications have been developed. Considering the highly integrated geometries of high-pressure die-castings (HPDC), it is a prerequisite that material models are developed in parallel to the alloy development to capture the mechanical behaviour of the castings. Figure 8(b) shows a diagram of force as a function of displacement during Arcan testing of AlSiMgMn HPDC material characterizing its fracture and crack propagation behaviour.

10. Advanced Multi-Material “MM” Design Concepts

Advanced design concepts have been developed by the main European car manufacturers (OEMs) evaluating

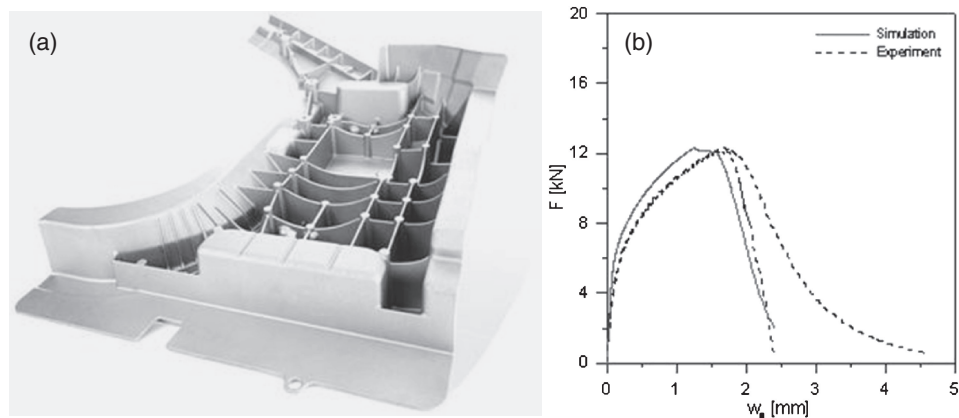


Fig. 8 Complex Aluminium automotive parts produced by high pressure die casting. (a) AlSiMgMn high integrity A-node casting (b) Fracture force evolution (simulations and experimentally measured crack propagation)

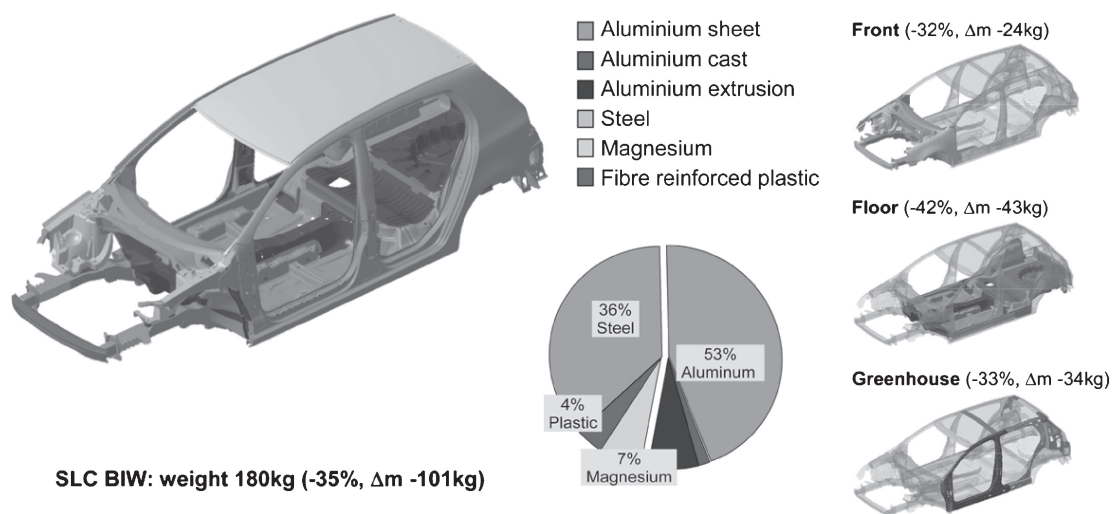


Fig. 9 Final BiW and selected materials for the innovative multi material SLC concept.³⁻⁵⁾

Aluminium solutions in competition with (new) steels, magnesium and plastics or composites. The multi-material “MM” design approach should yield the “best” material for the appropriate function, considering all technical, economical and ecological aspects, i.e. material and manufacturing costs (including suitable joining technologies), performance and safety, life-cycle-analysis “LCA” (incl. CO₂ emissions and recycling).²⁾ The “SLC” (full title: Sustainable Production Technologies of Emission Reduced Light weight Car concepts) produced a Golf V BiW as reliable benchmark for a mass produced car. The result was a 34% weight reduction within a cost increment of 7,8 €/kg saved, using assembling technologies feasible for a high volume production, (Fig. 9) and providing similar crash performance in a 5-star rating regime.³⁾

The SLC Project included a broad pre-competitive material and technology screening and testing. It generated newly developed special Aluminium alloys and reference studies for BIW structural application (in 5000, 6000 and 7000 alloys) with high strength, formability, energy absorption and excellent crash characteristics.^{11,12)} Suitable technologies were evaluated and developed by up-scaling of most promising and improving of existing Aluminium sheet and

warm forming technologies,⁸⁾ HPDC for complex structural parts, forming technologies, Aluminium-steel TWB’s for crash-beams, joining and assembling for multi-material high production.¹³⁾

The full body-in-white prototype was constructed by the consortium (Fig. 10) and is being displayed on numerous congresses and exhibitions (e.g. Ref. 5, 9)). It receives highest attention by experts and even the prestigious “InnoMateria award”.¹⁴⁾

11. Summary

Today’s European cars contain an average of 132 kg of Aluminium components and industry is working on new improved Aluminium alloys and solutions for automotive applications: In the body structure and for chassis and suspension parts, presently Aluminium is mostly used in sport and luxury cars, but they can also find their place in smaller mass produced cars. Especially designed and processed Al-Mg-Mn 5000 alloys and newly developed high Mg contents improve mechanical and corrosion properties, and roll clad materials provide innovative alternatives. For hang-on parts like hoods, doors, and fenders, precipitation

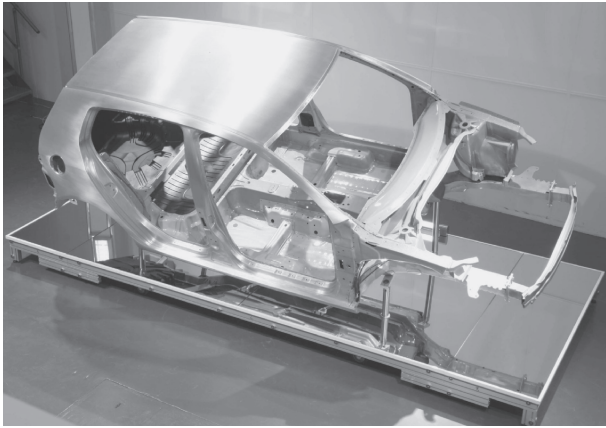


Fig. 10 SLC-Golf-V Body-in-White prototype, build with 64 vol% Aluminium.³⁻⁵⁾

hardening 6000 series alloys are established due to their excellent surface quality. New alloys meet highest requirements on formability and age hardening characteristics. Besides Aluminium new high strength steels, magnesium and plastics or composites were tested in advanced multi-material concepts that exploit the material potential of all light-weight materials. In the SLC project the “best” material for the appropriate functions in an overall cost efficient light-weight design was selected, with Aluminium was chosen by many European car manufacturers.

The SLC concept shows how any material, and especially Aluminium can be used for the car body structure giving a weight advantage of >30% without losing performance, providing cost effective light-weight solutions. Established or newly improved Aluminium alloys, e.g. high strength non heat-treatable (Al-Mg6) or high formable heat treatable 6000 and 7000 alloys are applied in various forms: As sheet used in the BIW, as hang-on panels and as chassis parts (seam welded tubes), extrusions in bumper beams and crash boxes, in space frames and where straight (or bended) profiles are needed and castings where complex forms with strong part integration is feasible.

Aluminium has proven to be the ideal light-weighting material allowing weight savings also in mass production within reasonable costs limits and without compromising safety.

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