A review on recent advances on aluminium for automotive applications focusing on passenger cars

Mohammad Iranmanesh*
IMIDRO, Tehran, Iran, P.O. Box: 1581614513

Abstract: Aluminium is remarkable for its low density, relatively low cost, light weight and high ability to resist corrosion. This material has many applications in industries. One of the common application of this material is in automotive industry. Recent development and advanced use of aluminium in passenger cars, focusing on 5xxx and 6xxx aluminium alloys has been discussed in the present paper. 5xxx and 6xxx aluminium alloys are characterized by their high strength and good formability, resulting in a mass reduction and improved crash worthiness.

Keywords: “super-light-car” “aluminium” “automotive” “alloy”.

Introduction
The European automotive industry is known worldwide as the technically most advanced and innovative. Based on economical and political pressure to reduce fuel consumption and CO₂ emission the efforts for light weighting in automobile design and constructions have increased significantly and specific solutions based on the intensive use of aluminium as modified or new alloys have been developed in the last decades [1]. 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). Full aluminium bodies allow weight saving of 70 to 140 kg (i.e. 30–40%) depending on the size of the car [2]. 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 [3]. 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. The European automotive industry has more than doubled the average amount of aluminium used in passenger cars during the last decade (Fig.1) and will do even more so in the coming years.

In parallel the European aluminium industry has developed and introduced numerous innovative light-weight solutions based on the established and further improved aluminium alloys [4-5] and optimized aluminium-oriented car design. One of the main advantages of aluminium is its availability in a large variety of semi-finished forms, such as shape castings, extrusions and sheet, all suitable for mass production and innovative solutions. Compact and highly integrated parts meet the high demands for high performance, quality and cost efficient manufacturability.

Aluminium is in fierce competitive with other materials, like novel steels recently developed, claiming back the light weight potential by higher strength alloys suitable for reducing wall thickness. Other competitor materials are magnesium, titanium and glass or carbon fibre reinforced plastics. The latter has developed further in the aerospace industries, now heavy R&D efforts are made suitable for mass production also for cars, especially innovative electro cars. Innovative car concepts have adopted the multi-material design idea to use for each function the “best” material available.

One of the main advances of aluminium is its availability in a large variety of semi-finished forms, such as shape castings, extrusions and sheet, all suitable for mass production and innovative solutions [6]. Compact and highly integrated parts meet the high demands for high performance, quality and cost efficient manufacturability.
Challenges involved here are mainly joining and surface treatment issues for which many suitable solutions have been developed. Aluminium semi-sheets are applied as castings, extrusions and sheet increases, e.g. in engine blocks and power train parts, space frames (e.g. Audi A2, A8, BMW Z8, Lotus Elise), sheet structures (Honda NSX, Jaguar) or as closures and hang-on parts (e.g. DC-E-class, Renault, Peugeot) and other structural components [3].

The average total aluminium content per car for European cars was 140 kg in 2013 [2]. Its distribution has been analyzed systematically as:

- Power-train (engine, fuel system, liquid lines): 69 kg (25 components analysed) in engine block and cylinder head, transmission housings and radiators.
- Chassis and suspension (cradle, axle): 37 kg (17 components analysed) in wheels, suspension arms and steering systems.
- Car body (body-in-white (BIW), hoods, doors, wings, bumpers and interiors): 26 kg (20 components analysed) in bonnets and doors, front structure and bumper beams.

This shows that for the body the most potential exists. Seen as one component the BIW is the heaviest part of a conventional car with a share between 25 and 30% of the complete car's weight, depending mainly on options installed, engine size, and integrated safety features [2].

Recently, development effort to apply wrought aluminium is becoming more active than applying aluminium castings. Forged wheels have been used where the loading conditions are more extreme and where higher mechanical properties are required. Wrought aluminium is also finding applications in heat shields, bumper reinforcements, air bag housings, pneumatic systems, sumps, seat frames, sideimpact panels, to mention but a few. Aluminium alloys have also found extensive application in heat exchangers. Until 1970, automotive radiators and heaters were constructed from copper and brass using soldered joints. The oil crisis in 1974 triggered a redesign to lightweight structures and heralded the use of aluminium. The market share of aluminium has grown steadily over the last 25 years and is now the material of choice for use in the automotive heat exchanger industry. Modern, high performance automobiles have many individual heat exchangers, e.g. engine and transmission cooling, charge air coolers (CACs), climate control.

2. Aluminium alloys for body-in-white applications

Up to now the growth of aluminium in the automotive industry has been in the use of castings for engine, transmission and wheel applications, and in heat exchangers. The cost of aluminium and price stability remains its biggest impediment for its use in large-scale sheet applications. Aluminium industry has targeted the automotive industry for future growth and has devoted significant resources to support this effort. The body-in-white (BIW) offers the greatest scope for weight reduction with using large amount of aluminium.

Recent developments have shown that up to 50% weight saving for the BIW can be achieved by the substitution of steel by aluminium [4]. This can result in a 20–30% total vehicle weight reduction when added to other reduction opportunities.

There are two types of design each of which has a different form philosophy in the use of aluminium. One is the extruded space frame exemplified by the Alcoa-Audi A8 (see Fig. 2), and the other is the conventional sheet monocoque architecture as used in most steel structures as by the Alcan-Ford aluminium intensive vehicle (AIV) (see Fig. 3). Each type has its merits: the space frame offers lower tooling costs by eliminating some stampings, whereas the conventional sheet monocoque offers established processes and low piece costs. The updated examples of these two types are Ford P2000 and Audi AL2.

Both of them could reduce weight about 40% on the BIW basis. The extruded space frame developed for Audi A8 is believed most appropriate for low volume production. The structure of Audi AL2 is a modified space frame with aluminium extrusions already developed for A8. Fig. 4 shows the Audi AL2 model with an all-aluminium body structure. In the AL2, there are fewer aluminium cast joints, which were extensively used in A8 since they are replaced with direct bonds. Aluminium extrusions in the AL2 are also made into as straight shape as possible. A comparison between A8 and AL2 models is made in Table 1, showing the efforts being made to reduce production costs and to up-scale the production volumes. It is also clear that, as the automotive companies work more and more with aluminium, simplification of design results in lower overall cost.

Fig.2 Aluminium extruded space frame BIW architecture, Alcoa-Audi A8.

Fig. 3 Alcan-Ford AIV sheet monocoque architecture.
formability. In Europe, EN-6016 is preferred and applied in gauges of around 1-1.2 mm. It shows a superior formability and filiform corrosion resistance and allows flat hems even on parts with local pre-deformation. However, the bake-hardened strength of 6016 is significantly lower than that of AA-6111 [6].

![Fig. 4 Audi AL2 with an all aluminium body structure.](image)

**Table 1 Comparison in space frame design A8 & AL2.**

<table>
<thead>
<tr>
<th></th>
<th>A8 (249 kg)</th>
<th>AL2 (153 kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sheet</td>
<td>71%</td>
<td>71%</td>
</tr>
<tr>
<td>Casting</td>
<td>15%</td>
<td>8%</td>
</tr>
<tr>
<td>Profiles</td>
<td>14%</td>
<td>21%</td>
</tr>
<tr>
<td>Straight</td>
<td>49%</td>
<td>84%</td>
</tr>
<tr>
<td>2D</td>
<td>34%</td>
<td>8%</td>
</tr>
<tr>
<td>3D</td>
<td>17%</td>
<td>8%</td>
</tr>
<tr>
<td>Spot-Welding</td>
<td>500</td>
<td>----</td>
</tr>
<tr>
<td>Clenching</td>
<td>178</td>
<td>----</td>
</tr>
<tr>
<td>SPR</td>
<td>1100</td>
<td>1500</td>
</tr>
<tr>
<td>MIG</td>
<td>70 mm</td>
<td>20 mm</td>
</tr>
<tr>
<td>Laser</td>
<td>---</td>
<td>50 m</td>
</tr>
</tbody>
</table>

### 3. Aluminium alloys used in automobiles

In the multi-material SLC design the contribution of the aluminium concern new alloys as well as alternative production methods for aluminium parts. Aluminium sheet is predominantly used for BIW panels and closures. Despite the existing "all aluminium vehicles" like Audi A8 and Jaguar XJ, aluminium in mass produced vehicles needs to reduce development time and other additional costs in new production methods and/or new alloys. The main aluminium alloy classes for automotive sheet application are the non-heat treatable Al-Mg (EN 5xxx series) and the heat treatable Al-Mg-Si (EN 6xxx series) alloy system, some especially tailored by variations in chemical composition and processing, e.g. Al-Mg alloys optimized for strength and corrosion resistance for use in chassis or Al-Mg-Si alloys applied for autobody sheets have been improved for formability, surface appearance and age hardening response. The specific properties and principal differences are illustrated in Fig. 5. The effects of varying alloy additions and process parameters as described in are well developed and controlled for enhanced performance and efficient manufacturing [6].

#### 3.1 Age hardening Al-Mg-Si alloys

6xxx series alloys contain magnesium and silicon. Current 6xxx alloys used for autobody sheets are AA6016 (Europe) and AA6111 (Americ) and, more recently, AA6181A was added for recycling aspects. In the US, AA6111 is often used for outer panels in gauges of 0.9-1.0 mm which combines high strength with good formability. In Europe, EN-6016 is preferred and applied in gauges of around 1-1.2 mm. It shows a superior formability and filiform corrosion resistance and allows flat hems even on parts with local pre-deformation. However, the bake-hardened strength of 6016 is significantly lower than that of AA-6111 [6].

![Fig. 5 EN-AW 5xxx and 6xxx alloys competing for car body sheet.](image)

In recent years alloy and processing modifications have been introduced to meet the increased requirements [6]. Higher strength alloys may allow outer panel thickness reductions with no loss of dent resistance, provided stiffness requirements are met. As paint-bake temperatures decrease, there is increasing demand for a significantly higher age hardening response. However, for some parts formability remains the major difficulty. Therefore special alloy modifications with either improved formability or strength have recently been developed by European aluminium sheet manufacturers and agreed upon as standards by the automotive industry.

#### 3.2 Non-heat treatable Al-Mg-Mn alloys

Al-Mg-Mn alloys show an optimum combination of formability and strength achieved by the mechanism of solid solution and deformation hardening due to their specific high strain hardening. Further improvement in properties required for specific applications (e.g. surface appearance, corrosion resistance, thermal stability) have been achieved by small additions of other alloy elements and/or modified processing routes [4], e.g. stretcher strain free ("SSF") sheet, avoiding Lüders-lines [5].

Non-heat-treatable Al-Mg-Mn alloys are applied in europe for automobile parts in larger quantities as hot and cold rolled sheet and hydroformed tubes, due to their good formability which can always be regained during complex forming operations by inter-annealing where quenching is needed for age hardening. In chassis parts or wheel applications the benefit is two fold since the weight reduction in the unsprung mass of moving parts additionally enhances driving comfort and reduces noise levels.

A well-established alloy with high magnesium content, AlMg5Mn (A5182), is used for high strength and complex stampings. For 5xxx alloys containing >3% Mg
the precipitation of \( \beta \)-Mg5Al8 particles at grain boundaries can result in susceptibility to intergranular corrosion cracking (ICC) by long term exposure at \( >80 \)°C. For these conditions special high-Mg-content alloys have been developed with a good compromise for sufficient strength and ICC resistance. For all other cases special high Mg alloys (\( >6\% \)Mg) have been introduced which show high strength and strain hardening, thus also enhancing formability. Al-Mg-Mn alloy sheet has also been successfully applied or is currently being tested in many parts for structural support, pedal boxes, heat reflectors, lever arms e.t.c... Al-Mn EN-AW 3xxx alloys are applied for heat-exchangers which is another success story of aluminium sheet and extrusion applications that started in Europe many years ago. It is an increasing market with intensive R&D, established for advanced light-weight technology for radiators and air conditioning systems in cars (and elsewhere) world wide.

3.3. 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 aluminium space frame, Fig. 6 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.

3.4. 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. 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 [6]. 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.

4. Aluminium competition with other lightweight materials

The new BIWs concept of “Multi-material designs”, consists of a suitable application of any available material, under the principle idea to use the “best” material for each function, which means aluminium applications together with high and ultra-high strength steels, magnesium and plastics or composites. An additional major goal is to achieve an overall cost-efficient lightweight design. This is the main objective of the “Super Light Car” (SLC) project [4-5], Sustainable production technologies of emission reduced light-weight car concepts were initiated in 2004, started in 2005 and ended in 2009. 38 partners: 7 OEMs (CRF, DC, Porsche, Renault, Volvo, Opel and VW as project coordinator), 10 R&D companies, 10 suppliers, 8 universities and 3 SMEs, came together to evaluate current and new technologies and to design and construct new lightweight car with the motivation to design and construct a weight reduced vehicle structure to a reduction in CO₂ emissions and fuel consumption as a global ecological and local economical and customer benefit. The SLC car should be suitable for large series productions as an economically producible advanced material vehicle structures [5]. Two important boundary conditions are to be taken into account.

1) Affordable cost

Mass is a major factor, besides aerodynamic drag, rolling resistance, engine efficiency, electric consumption, that contribute to CO₂ emission. Investment will be target in the factor that yields a maximum CO₂ reduction per invested Euro so for each factor; a maximum allowable cost increase can be calculated. It strongly depends on the material selection and the slope must be decreased by an intelligent multi-material approach that can meet the increasing limits of the CAFÉ regulations on an acceptable level (Fig. 5). For mass reduction, the cost target for SLC is specified as <5 €/kg mass saved. The costs are calculated including material cost, production cost, investment depreciation and recycling revenues. An effective cost model has been developed based on the traditional production methods for the present steel body taking into account the new materials, parts with integrated functions and production methods.

2) Optimum performance

In order to make an appreciable contribution to worldwide CO₂ reduction, the reference BIW selected is a high volume car (Golf V). The present Golf V meets the stringent European standards on crash, obtaining a 5-star rating in the Euro NCAP test. This is achieved in part by making extensive use of high strength steels. Steel, however, has a limited mass saving potential of 55 kg. The challenge for the SLC project is to see if other materials can provide similar crash performance and 5-star rating for a mass optimised BIW.

5. Aluminium in SLC body concept

The SLC project has first designed three different concepts (Fig. 9) with priorities for mass reduction through specific material design and joining methods and part count and cost targets (material, part production and joining) [6]:

1) A steel intensive “light-weight” concept (promoted by Arcelor) with increased utilization of high strength steels delivered a maximal mass reduction of 55 kg (19%) with minor additional costs of <2.5 €/kg. The highlights here are a strut tower in X-IP 1000 steel, a tunnel in hot-formed high strength steel (Usibor 1500), bodyside and B-pillar in dualphase-steel, a roof in Quietsteel and fender in Usilight.

Fig 9 Three basic SLC-body multi-material concepts.

2) An intermediate light-weight concept called Ultra Light Body Concept (ULBC), which achieved a further mass reduction of 77 kg (27%) but with higher (but limited) additional costs (<5 €/kg). Here the highlights are a longitudinal rail in FeMn steel tailored welded sheets, a suspension-strut mount as Al-diecast (Silafont 36), a tunnel in FeMn-blank steel, a rear wheelhouse and an inner B-pillar in Al-diecast and a roof in Al-sheet. In this light-weight concept a new multi-material design was applied for a significant mass reduction, using steel in the loading paths and lightweight design materials such as aluminium for the front end and roof with cast parts of high functional integration.

3) An intensive light-weight concept called Super Light Body Concept (SLBC), which achieved major mass reduction of 112 kg (39%) with the highest additional costs (<10 €/kg). Here highlights are a longitudinal rail in high strength Tripl800 steel in tailored welded blanks, a strut tower as Mg-diecast, floor panels in Al- and Mg-sheet, a wheelhouse and rear longitudinal rail in Al-sheet, the inner B-pillar in Usibor (PHS) steel and a roof in Mg-sheet. The final SLC-body concept (Fig. 10) shows an optimum between mass reduction of 95 kg (34%), i.e. a mass saving of 41% vs reference (from 65 kg to 110 kg) and an additional part costs of 5 €/kg. It has a magnesium roof and a steel floor frame (i.e. lighter on top than underneath) and a torsion ring in the side structure made of form-hardened high strength steel combined with an aluminium sheet frame. For the inner B-pillar TWB steel
sheet is used with an external aluminium skin. Aluminium is used as sheet panels and as extrusion in front rails, bumper, crash elements, in the rear underbody rail, and in the wheelhouse structure as HPDC (high pressure die cast).

In the multi-material SLC design the contribution of the aluminium concerns new alloys as well as alternative production methods for aluminium parts. Aluminium sheet is predominantly used for BIW panels and closures. Despite the existing “all aluminium vehicles” like Audi A8 and Jaguar XJ, aluminium in mass produced vehicles needs to reduce development time and other additional costs in new production methods and/or new alloys [4]. Innovative aspects investigated are as follows.

1) Heat forming is a new technique for producing complex aluminium tubular shapes using internal gas pressure to form hollow bodies or tubes within a warm environment [6]. It provides a competitive alternative to hydro- or superplastic forming (SPF).

2) Tailor welded blanks (TWB) are a mature product for casting in large volume applications, aluminium solutions are most cost effective. Castings will be applied in areas where strong part integration is feasible. Extrusions can be easily applied as straight profiles, but also forming of an extruded profile is a competitive process for high volumes, e.g. as bumper beams as used in the SLC prototype car.

Conclusions

Due to its low weight, good formability and corrosion resistance, aluminium is the material of choice for many automotive applications such as chassis, autobody and many structural components. Aluminium alloys tailored by suitable variations in chemical composition and processing best fit many requirements, like the non-heat treatable Al-Mg alloys used in chassis optimized for superb resistance against intercrystalline corrosion and concurrent high strength or the heat treatable AlMgSi alloys for extrusions and autobody sheet modified for improved age hardening response during the automotive paint bake cycle. With a sound knowledge about the specific material properties and effects excellent light weight solutions for automotive applications have been successfully applied by the European automobile industries. Intensive R&D and continuous collaboration of material suppliers and application engineers provided optimum solutions for sometimes contradicting aspects of the specific requirements, e.g. for the specific material selection and optimum combinations of strength and formability. Material specific processing routes and individual solutions have been developed in close cooperation with OEM partners and suppliers. Applying the full knowledge about the physical processes involved and the microstructure / properties correlation a tuning of properties is possible in order to produce optimum and stable products required for the high demands in automobile applications. The examples given for the successful prove the major breakthrough in automotive applications for aluminium that has been achieved during recent years by developing innovative light weight and cost efficient solutions. With the reference of the SLC project results it is expected that in the near future the use of aluminium with specifically improved properties will grow in many automobile applications meeting the increased economical and ecological demands. Due to the positive experience gained in the project and from the former successful applications, its volume fraction used in cars of all classes and all sizes will grow significantly. The SLC concept shows clearly that aluminium can be used for the car body structure and that there can be a mass advantage of at least 30% without losing performance. For most parts the present grades used for exterior panels can be applied. In some cases, when very high strengths are demanded, 7xxx series alloys can be used to maintain this significant mass advantage. For large volume applications, aluminium solutions are most cost effective. Castings will be applied in areas where strong part integration is feasible. Extrusions can be easily applied as straight profiles, but also forming of an extruded profile is a competitive process for high volumes, e.g. as bumper beams as used in the SLC prototype car.

References