# Design – Design with Aluminium

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2 Design with Aluminium

2.1 Introduction

2.1.1 Holistic design makes the difference

The main reason for introducing aluminium into vehicle components, structural modules and full vehicle structures is to achieve a significant weight reduction compared to a conventional design. Depending on the specific application, the weight reduction potential ranges between 25% and over 50%. Significant weight reduction possibilities exist even compared to a modern vehicle body designed using advanced high strength steel grades. In a recent study by ika Aachen “Stiffness and Crash Relevance of Car Body Components”, the strength and stiffness relevance of typical components of a state-of-the-art, reference compact class car body including closures were quantified for selected global crash and stiffness load cases. Using these values, the resulting weight reduction potential of intensive high-strength steel usage was assessed to be approximately 11 %. For the same reference car, the weight reduction potential is approximately 40 % when steel is substituted by optimized aluminium materials. The finally realised weight reduction, however, is often not the lowest technically achievable weight. Generally, cost considerations and/or production issues are an overriding issue. In many cases, the opportunities offered by appropriate aluminium solutions are also exploited to increase the vehicle stiffness to obtain a performance enhancement at a modest increase in cost and weight.

At the same time, the aim must be to develop easily manufacturable and cost effective designs that meet the required structural criteria. Competitive use of aluminium in lightweight automotive structures requires an aluminium-oriented design approach. A simple material substitution does not result in an optimum solution from a technical, economical and ecological point of view. There are only few exceptions, especially if one or more of the fundamental properties of the substituting material is the dominant requirement for the specified application (e.g. the outstanding thermal properties of aluminium compared to steel in case of a heat shield).

In the development of aluminium-oriented designs, consideration must be given to the total system from the forming of the single components to the final assembly and surface finishing. A total system approach is particularly important for structural modules and full vehicle structures, since structurally efficient joints can enhance structural stiffness, crash performance and fatigue endurance of the car body, while a plurality of joining systems may primarily add cost and even lead to a reduced structural performance of the vehicle.

Genuine aluminium designs look for solutions where the opportunities offered by aluminium-specific fabrication technologies, such as the extrusion of hollow and/or multi-chamber profiles or the high quality casting of thin-walled, intricately shaped components, can be exploited to the maximum. The integration of additional functions into a component and/or the reduction of the number of components (part integration) offer good chances for cost-efficient aluminium design concepts. In addition, the selection of joining methods particularly suited for aluminium, which provide punctiform (self-piercing riveting, friction stir welding, etc.) or continuous joints (structural adhesive bonding, laser welding, etc.) may provide significant technical and cost advantages.

The most common design criteria for a vehicle structure are strength (crash performance), stiffness, and fatigue endurance, with stiffness usually being the most challenging to meet because aluminium has a lower elastic modulus than steel. The Audi space frame structure shown below in its first version is an example of a vehicle structural design where a considerable enhanced stiffness was achieved in addition to a lower weight and - based on
the target production volume - at acceptable cost.

For high production volumes, car body structures mainly based on aluminium sheets are most cost-efficient. The monocoque body structure of Ford's P2000 PNGV prototype shown below is an example of a structure where structural adhesive bonding and tailor-welded blanks have been used to minimise weight while maximising structural stiffness.
2.1.2 The cost of lightweighting with aluminium

The application of aluminium in the car body offers significant weight reduction potential, but in general the saved weight is also connected with some additional cost. Compared on a pure mass basis (i.e. price per kg), the aluminium price is well above that of steel. However, depending on the specific applications, it is more meaningful to compare the material price on a volume basis or based on the applied surface. But even in such comparisons, there is usually a clear cost difference between the two materials. In addition there may be some process-related extra costs for aluminium within a traditional automobile manufacturing plant which are primarily due existing equipment not optimally suited for aluminium processing and/or missing aluminium processing know how and experience.

Detailed studies showed that from a user point of view, extra costs caused by lightweighting are accepted up to a certain amount. The level of the acceptable extra cost depends on many factors (type of car, production volume, etc.), but in particular on the specific aluminium application. The resulting weight reduction is of particular interest for components and structural modules where an additional customer benefit can be realised, for example improved driving performance of the car (more equal axle load distribution, lower center of gravity, smaller unsprung masses) or a easier handling of hang-on parts (doors, tailgates, hoods, etc.). In general, the value of lightweighting decreases from the front to the rear and from top to bottom of the car body.

Therefore the development of automotive design and manufacturing concepts which are optimally adapted to aluminium - and thus also most cost-effective - has highest priority. A significant cost reduction can be realized by the application-orientated selection of design principles and fabrication technologies. Significant cost reduction potentials are present in the total production chain of the car body when the specific benefits of aluminium as a construction material are fully capitalised by the skillful exploitation of the advantages of aluminium in an overall system approach. Such considerations are particularly important when applying the sheet design concept which is most favourable for large volume production. Furthermore, as a result of the reduced body weight, additional secondary weight and cost saving potentials possibilities may exist in the powertrain as well as in the chassis and suspension.

In addition, a substantial contribution to the reduction of the total life cycle costs of an aluminium car will be provided by the recycling of the end-of-life vehicle. Today, a significant part of the proceeds from the end-of-life treatment step originates from the recycling of the metals contained in the vehicle - in particular the aluminium fraction. Unless dismantled before the shredder operation, the non-metallic materials end up in the automobile shredder residue (“fluff”) which must usually be disposed liable to pay costs. Therefore, the growing application of aluminium in the automotive market secures in the long term also the economical treatment of end-of-life vehicles. Aluminium is almost completely recovered and predominantly used again in the form of casting alloys in the fabrication of new automobiles (engine blocks, cylinder heads, transmission cases, pistons, suspension parts etc.). The processing of the recovered aluminium scrap forms the basis of an separate, economically important branch of the aluminium industry with highly developed processing techniques and methods meeting all environmental standards.
2.1.3 Mixed material design

The partial or complete substitution of steel sheets in the car body by lighter aluminium products takes place:

- in the form of individual hang-on parts or structural modules integrated into a car body otherwise made from steel, preferentially where the reduced weight also offers the realisation of additional advantages or
- by the consistent aluminium lightweight design of the car body (complete or largely, e.g. an aluminium front section).

Apart from the intensified use of aluminium hang-on parts, aluminium sheet components with structural functions will be integrated more and more into steel car bodies in the future. The extent of such a mixed material design can vary considerably and reach from individual aluminium structural modules in a steel body to an aluminium body with a few steel attachments. The importance of the all aluminium car body will grow in future in particular for upper class models and sports cars in niche applications and for small series production. However, in mass production, mixed material constructions where steel provides the strength and the stiffness of the body structure and aluminium sheets are the preferred material for closure parts will be the dominating body design concept.

For hang-on’s, the advantages of aluminium can be easily realised without a need for substantial changes in component design or manufacturing. Their integration into the steel body offers relatively little problems and aluminium components fulfill at least the same performance requirements as their steel counterparts.

More difficult is the integration of structural aluminium components or modules into a steel body. There are two major design and production issues:

- The coefficients of thermal expansion of aluminium and steel differ distinctly. Smaller temperature variations as observed for example in the car body under normal service conditions do not present any difficulties. But problems may arise if a mixed aluminium/steel body is subjected to large temperature changes, such as for example in the lacquer bake hardening step which takes place at temperatures around 180°C. Proper design measures and carefully selected joining parameters, however, often enable a solution of the resulting issues.
- The potential appearance of galvanic corrosion effects must be considered in particular in connection with mixed material car body structures. It is normally better to isolate steel as the “nobler” contact partner (from an electro-chemical point of view) using a non-conductive coating. If the less nobler partner is coated, there is the danger that a local damage in the coating will lead to an intensified corrosion attack due to the concentration of the attack on a much small surface area.

In practice, there are generally appropriate solutions for these corrosion protection and thermal load cycling problems. But a detailed analysis of the specific situation and careful consideration of the potential solutions is always required for multi-material automotive systems, i.e. mixed material car bodies, some powertrain assemblies as well as chassis structures.

Additional attention must be given to the treatment of end-of-life vehicles. Disassembly and separate recycling may be evaluated for larger components. The alternative is shredding and subsequent material separation. Shredding is currently the preferred method for the recycling of automobiles. The recycling industry is equipped to automatically separate ferrous and non-ferrous materials. Joint seams containing aluminium and steel will be usually found in the steel bin after separation. Aluminium is generally considered beneficial for secondary steel-making operations since it is commonly added to deoxygenate in order to produce aluminium-
killed (AK) steel. If in sufficient quantity, aluminium may also deliver the added benefit of combining with nitrogen to form aluminium nitride, which has the effect of pinning grain boundaries during subsequent processing. However, steel is an undesirable impurity for aluminium.

Including these issues into early design phases can considerably improve manufacturing costs related to the management of build tolerances and the end-of-life ecological impact of multi-material body structures.

**Audi TT ASF®, a sheet-intensive hybrid space frame combining an aluminium structure with a steel sheet assembly in the rear**

Source: Audi
2.1.4 The role of production volume

The combination of all possible aluminium product forms opens a wide variety of design concepts, characterized by functional modularity and different final assembly needs. However, the decisive factor in the selection of the optimum design concept - and as a result the applied aluminium product forms - is generally the envisaged production volume. High volume production looks for minimum material (component) cost and low assembly cost, but can afford relatively high investments both in tools and manufacturing equipment. In contrast, low volume production asks for minimum investment cost whereas component and assembly cost play a less important role. Thus for low volume production, hybrid structures using castings and extrusions in addition to stampings provide a cost effective way for achieving efficient structural assemblies.

The aluminium structure of the Ferrari Modena incorporating straight and slightly bent extrusions, some castings and few, fairly simple sheet parts is an excellent example of an optimized design for low volume production.

In particular the aluminium extrusion technology with its relatively low tooling cost lends itself to the low volume production of automotive components. This is valid in particular for machined, straight and/or two-dimensionally bent extruded parts. However, more complicated subsequent operations (e.g. hydroforming for improved geometrical tolerances) may add significant costs. Most interesting in this respect are also high quality aluminium casting technologies (i.e. sand casting, high pressure die casting, etc.) due to their inherent competency to produce components in fairly complex shapes.

On the other hand, the tooling cost for conventional sheet stampings are in most cases quite significant and need to be spread over a large volume in order to be competitive with other aluminium part forming methods. Consequently, depending on the planned production volume, the various aluminium product forms can be used in varying proportions, sizes and
shapes. In addition, the aluminium components can also be combined with other materials (stamped steel sheets, plastic and composite parts and even magnesium castings).

In addition, many other factors have to be considered when designing cost effective, genuine aluminium automotive structures and components for low, medium and high volume series. These considerations may lead to various design solutions resulting from the need to balance all the competing product requirements as well as the various manufacturing techniques with their specific opportunities and constraints.

As an example, a range of special aluminium sheet forming methods based on the use of active media are of interest for small series and niche applications. Their aim is an extension of the conventional forming limits of aluminium materials and/or to take into account manufacturing aspects looking for cost efficiency (in particular reduction of the tooling cost). Forming methods like hydromechanical sheet forming, rubber press forming and superplastic forming require, for example, only a mould half and are therefore highly suitable for lower production volumes.
2.1.5 Integration of functions and parts integration

Aluminium extrusions and castings offer great possibilities to exploit the benefits of a reduction of the number of parts or an integration of additional functions into structural components. But also the aluminium sheet technology offers specific opportunities. When designing components and structures in aluminium, it is most important to take advantage of the all the available product forms to reduce both part mass and cost. A reduction of the number of individual parts that have to be made and assembled reduces the necessary tooling, handling and assembly operations, and the elimination of joints will also improve the overall dimensional accuracy, fatigue durability and structural stiffness.

a) Extruded aluminium sections

Extruded aluminium profiles are two-dimensional design elements with the advantage that there are little design limitations with respect to the complexity of the cross section (geometrical design, variation of wall thickness, multi-chamber cross sections, additional flanges, etc.). Subsequent forming (e.g. bending, hydroforming, etc.) and machining processes also allow for limited three-dimensional design capability. These possibilities can be fully exploited in the car body structure. Interesting possibilities are the incorporation of integral webs into extrusions, e.g. to increase their stiffness or energy absorption capacity, and/or the addition of external flanges to provide a connecting surface for other parts of the assembly. For aluminium profiles, the strength requirements are very often not the limiting factor as the minimum wall thickness is mainly determined by the manufacturability of the profile (“extrudability”).

The figures below illustrates how a single roof rail extrusion can replace a three component stamped and welded assembly while providing a flange for connecting onto the roof and another for the door window seal.

Stamped sheet and extruded roof rail sections illustrating integration of functions in the extruded version

Furthermore, the unique advantages of the aluminium extrusion technology proved to be the decisive factor to achieve the present market penetration of aluminium in crash management systems for automotive applications:
Proper multi-chamber cross section design enables closely controlled energy absorption characteristics.

Multi-wall profiles offer high redundancy if a wall fails in a crash (most important to ensure the envisaged crash behaviour also in non-standard crash situations).

Cross section design with tailored wall thicknesses allows the application of thicker walls only where required for additional lightweighting.

Multi-chamber aluminum profiles with an appropriate cross section design for optimum crash absorption characteristics

Source: Constellium

Side impact beam with a load-optimized cross section optimized for minimum weight

Source: Constellium
b) **Aluminium castings**

Aluminium castings, in particular high quality thin walled structural castings produced by sophisticated casting techniques, enable single cast parts to replace components and sub-assemblies constructed from multiple stampings, again eliminating the need for joining operations and thus improving dimensional accuracy, stiffness and part integrity.

Typical applications are cast nodes and large structural components in space frame car body designs. However, while castings allow a single complex part to be made serving several functions, considerable care must be taken in production to achieve the required ductility and fatigue endurance. Closely controlled special casting techniques and an elaborate tool design based on finite element analysis and numerical modelling of the filling and solidification process must be used to ensure that a high freezing rate and low porosity are obtained in the structurally critical regions.

![Lower rear suspension control arm produced in A356 alloy by low pressure die casting](image)

The lower rear suspension arm casting in A356 alloy for the Lincoln Mark VIII shown here replaced a ductile iron one which in turn replaced an assembly of 17 steel stampings.

Today, thin walled high pressure aluminium die castings are established structural elements for car body constructions. Apart from the availability of a top quality pressure die casting process, the decisive factors for the successful application of such structural die castings in car body design are the correct choice of the alloy composition and the applied heat treatment. A illustrative example is the MIG welded sub-module from the front end of the Audi A2 shown below. The sub-module consists of the strut dome and the upper and lower front longitudinal members, an assembly which is subject to high structural and crash loads. Such structural assemblies produced by appropriate high quality vacuum high pressure die castings - which may also include other aluminium components - are extremely crashworthy. They can be joined by various welding (MIG, Laser or hybrid welding), mechanical joining techniques (bolting, riveting incl. self-piercing rivets) as well as adhesive bonding and easily integrated in a mixed material body concept.
c) Aluminium sheets

The integration of functions and parts is, up to a certain amount, also possible with aluminium sheets. A possibility to achieve the integration of functions into sheets is the development and application of tailored blanks, i.e. aluminium blanks where the material characteristics are locally varied in a controlled manner ahead of the stamping operation. Tailored aluminium blanks can be produced by different techniques, e.g. by tailor rolling, tailor welding or local thermal treatment. Well known are tailor welded blanks (TWB), whereby a blank consisting of more than one gauge and/or alloy has been produced by butt welding the appropriate sheets together.

The use of tailor welded blanks has become commonplace in the design and building of stamped steel car body structures and is more and more becoming a possibility for aluminium components and structures. Also possible are hybrid aluminium/steel blanks. Tailor welded blanks are for example applied when a heavier gauge is required in a specific area to provide the required strength and stiffness, while the rest of the panel can be made of a lighter gauge, thereby facilitating the stamping of the part and reducing the cost and weight. The example shown below is a rear inner body-side stamping for the Ford P2000 which was stamped from a TWB in AA 5754 sheet at 2.0 mm in the door region and 1.0 mm in the trunk region.

Rear inner body side stamping for the Ford P2000, stamped from a tailor welded blank

Source: Novelis
Other possibilities are offered by the application of roll forming, a sheet forming process with rotary tool movement. During the roll forming process, a flat strip of sheet is transported through a number of powered metal forming stands as well as unpowered side rollers and is thereby shaped into the desired form. Closed cross-sections are produced by an integrated welding operation. Roll formed steel parts have been used in various applications in the automobile industry, but the process can also be applied to aluminium. The most important advantage of roll forming lies in its high production capacity which is directly linked to its economic efficiency. Roll formed sections can fulfil - to a certain degree - similar functions as extruded aluminium sections.

Examples of roll formed cross sections

Source: Tillmann Profil

New roll forming concepts permit the realization of completely new shapes, the use of different wall thicknesses in one cross-section, and even variable cross-sections within the entire profile length.

Additional opportunities are offered by multi-alloy aluminium sheets where the surface and core material can be independently engineered while maintaining a consistent high quality interface between the different layers. In a multi-alloy aluminium sheet, a high-strength core material can be combined with a extremely good formable surface layer. This overcomes the hemming problem of high strength aluminium materials using tight radii. As another example, a core alloy highly suitable for the envisaged car body application, but unfortunately does not exhibit the required corrosion resistance, can be covered with a suitable alloy for corrosion protection. The technology can also be used to tailor the strength and crash performance of an aluminium sheet precisely to the requirements of individual structural applications.

Multi-alloy aluminium sheet products have been traditionally produced by roll bonding where the clad layer is bonded to the core by rolling at elevated temperatures, a tedious and costly process with a number of quality risks. With the Novelis Fusion™ technology, an innovative casting technology for multi-alloy rolling ingots has been introduced which provides a cost-efficient way to produce such composite aluminium sheets. Novelis Fusion™ AF350 sheets combining a high formability AlMg5 core material with a corrosion resistant AlMg1 alloy
surface enable for example the realisation of highly demanding applications such as the one-piece inner door panel stamping for the BMW 5 series models.

One-piece inner door panels for BMW 5 series models made from Fusion™ AF350

Source: Novelis
2.2 Comparison to steel

Steel sheets in various grades, from highly deep-drawable qualities to ultra high strength steels, are today the dominating material in the automotive industry. Recently developed steel grades enable further increases in the combination tensile strength and total elongation, so that steel materials can meet even higher requirements.

![Total elongation and tensile strength of different steel grades](image)

**Source:** Aleris

In the diagram shown above, the aluminium alloys applied in the automotive design can be found below the steel “banana”.

However, strength is not the only material parameter to be considered in a car body design. Both the density and stiffness of aluminium are about one third those of steel. This has significant effects. In a weight-specific strength comparison (see below), aluminium alloys exceed the strength level of the low strength steels and can easily compete with advanced high strength steels. This is even more evident when the weight-specific comparison is made on the basis of the yield strengths of both materials. High strength aluminium alloys currently used for aerospace applications can even meet the strength level of advanced high strength steels on a weight-specific basis. On the other hand, the modulus of elasticity of aluminium and steel is – compared on a weight-specific basis – similar.

In an evaluation of the application of different materials on the mass of vehicle body parts, some fundamental parameters like bending and torsion stiffness as well as tensile strength have to be considered. These parameters are a function of material-dependent parameters, like the modulus of elasticity (E), the material density (ρ), the tensile strength (R_m) and the modulus of shearing (G), dedicated to the shape of typical body components:

- Bending stiffness parameter: \( \frac{\sqrt{E}}{\rho} \)
- Tensile strength parameter: \( \frac{R_m}{\rho} \)
- Torsion stiffness parameter (open profile): \( \frac{G}{\rho} \)
- Torsion stiffness parameter (closed profile): \( \frac{G}{\rho} \)
Three-point bending parameter: $\frac{R_m}{\rho}$

These parameters are valid under the assumption that the basic design of the specific component is independent of the material. However, if the design of the component is changed, significant changes are possible.

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**Weight specific comparison of the mechanical properties of aluminium and steels**

*Source: Aleris*

The following table shows typical mechanical properties for some representative aluminium and steel automotive sheet materials to compare and contrast their respective properties.

**Comparison of aluminium and steel mechanical properties**

<table>
<thead>
<tr>
<th>Material</th>
<th>Modulus $\times 10^2$ (MPa)</th>
<th>Density $\times 10^2$ (kg/m$^3$)</th>
<th>YS (MPa)</th>
<th>UTS (MPa)</th>
<th>$\varepsilon_%$</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA 5754 - O</td>
<td>70</td>
<td>2.7</td>
<td>110</td>
<td>220</td>
<td>23</td>
</tr>
<tr>
<td>AA 6016-T4</td>
<td>70</td>
<td>2.7</td>
<td>100</td>
<td>205</td>
<td>27</td>
</tr>
<tr>
<td>AA 6111-T4</td>
<td>70</td>
<td>2.7</td>
<td>135</td>
<td>275</td>
<td>25</td>
</tr>
<tr>
<td><em>After 2% strain and simulated paint bake treatment:</em></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AA 6016 - T6x</td>
<td>70</td>
<td>2.7</td>
<td>220</td>
<td>270</td>
<td>16</td>
</tr>
<tr>
<td>AA 6111 - T6x</td>
<td>70</td>
<td>2.7</td>
<td>260</td>
<td>330</td>
<td>19</td>
</tr>
<tr>
<td>Fe Pi5</td>
<td>205</td>
<td>7.65</td>
<td>155</td>
<td>295</td>
<td>49</td>
</tr>
<tr>
<td>IF Steel</td>
<td>205</td>
<td>7.65</td>
<td>210</td>
<td>365</td>
<td>36</td>
</tr>
<tr>
<td>DP Steel</td>
<td>205</td>
<td>7.65</td>
<td>335</td>
<td>500</td>
<td>24</td>
</tr>
</tbody>
</table>
2.2.1 Design criterion: Stiffness

In the particular load case of sheets in bending under a local load (closures and BIW applications), in order to meet a specific requirement for limited strain, it is necessary that:

\[
\frac{t_{\text{alu}}}{t_{\text{steel}}} = \frac{3 \sqrt{\frac{E_{\text{steel}}}{E_{\text{alu}}}}}{1.44}
\]

and therefore:

\[
\frac{\text{mass}_{\text{alu}}}{\text{mass}_{\text{steel}}} = 1.44 \cdot \frac{\text{density}_{\text{alu}}}{\text{density}_{\text{steel}}} - 1.44 \cdot \frac{2.7}{7.8} = 0.5
\]

This means that the sheet thickness must be increased by a factor of 1.4. However, the aluminium sheet is in the load case bending stiffness at equal performance still 50% lighter.

Consequently, aluminium automotive sheet can replace steel in closure panels with a 40-50% weight saving. The combination of the strength of aluminium with its low density results in a higher strength to weight ratio than steel, and thus enables significant weight reduction where strength is the design limiting criterion.

More generally, regarding bending stiffness and torsion stiffness, this relationship is valid for flat sheets and open profiles. In structural applications, an open aluminium profile requires 1.4 times more package space, but reduces the mass by 50% in reference to a steel profile with equal performance.

On the other hand, for the same bending stiffness and torsion stiffness, the wall thickness of a closed aluminium tube or rectangular closed profile has to be increased three times compared to that of a similar steel product. This also means that the aluminium and steel versions have the same weight. Thus in structural applications, due to the different elastic moduli, no weight saving is possible for individual tubular and box beam sections when the external dimensions are constrained - or if the steel thickness is not near its bottom limit for the section.

However, the many possibilities to vary the geometry of aluminium extrusions and cast parts in a controlled manner, in particular the local variation of the wall thickness of an aluminium extrusion still offer some benefits in design. Looking at the tip reflection in cantilever bending:
The above example shows the beneficial effect that can be obtained by using the aluminium extrusion technology to place the wall thickness where it is needed in this section in order to improve stiffness in a given direction, even if outside dimensions are fixed. The shown results can be considered as the minimum case since the load is only applied to the vertical walls. A greater difference can be expected if the load is applied to the top and bottom surfaces.

However, when comparing with steel tubes, it is very difficult to obtain a weight reduction with aluminium. As the thickness of the top and bottom walls increase, the material moves towards the neutral axis of the beam where it is least effective for bending stiffness:
The situation is completely different as soon as the package space can be changed, i.e. when the cross section of the profile can be varied. The most effective method to match the stiffness of a steel beam member in bending is to increase the beam depth.

The above example shows that similar bending stiffness can be obtained by making the aluminium box twice as thick and 20% deeper than the steel reference box. The weight implications are shown in the following:

For example, if the wall thickness of the aluminium and steel tube are kept the same, but the diameter of the aluminium tube is increased, again weight savings up to nearly 50% are possible. The following diagram illustrates how the section height and thickness for a rectangular aluminium box beam can be selected to provide equal section stiffness to a geometrically similar steel beam and yet provide significant weight saving.
This analysis shows that the selection of the correct design parameters is most important regarding the bending and torsion stiffness of a structural vehicle body part. With respect to bending stiffness, it is obvious that the closed tube and the rectangular hollow profile have a better bending stiffness than a flat sheet. An enormous decrease of the cross section area and therefore a significant mass reduction is possible by the application of these two profile types in comparison to a flat sheet. In this case, the best result can be achieved with the round tube.

If the package space is given, i.e. if a change of the outer dimensions of the tube or profile is not possible, the substitution of steel by aluminium does not allow a weight reduction. In fact, the application of aluminium instead of steel will lead to a slight weight increase. Therefore it is most important that the dimensions of a body part can be changed. Aluminium profiles always have higher packaging demands than a comparable steel profile. If the correct design parameter is changed, the substitution of steel by aluminium will lead to a reduction of the part weight in combination with a slight increase of its thickness or height. If the package can be changed and the maximal possible weight reduction (about 50 %) should be realized, the package demand increases by a factor of two times for round tubes as well as hollow rectangular profiles.

As a result, in new designs, it is possible to achieve significant weight savings and/or a higher stiffness since beams and box members can be optimally sized for aluminium and proper allowance can be made in the location of other components to accommodate the larger section sizes required. But the decision for an aluminium-adapted design concept must be made in the beginning. Generally, the structural package space is defined early in the design of a car because of the needs to accommodate the passengers and other automotive systems and to take into account the styling of the car, its ground clearance, etc.

When aluminium is being substituted for steel in an existing component or structural design, there is usually much less scope for accommodating larger beams. Nevertheless, in complete structures consisting of a combination of beams, box sections, and shear and closure panels, an increase of the aluminium sheet thickness of approx. 50% over the design steel gauges will yield at least equivalent bending and torsional stiffness at a weight saving of 40 - 45%, depending on type of panel and joining system used.

The figure below shows the body structure of the Ford AIV where the aluminium structure was based on a steel production design, yet achieved a higher stiffness with a 47% weight saving.
Aluminium body-in-white structure of the Ford AIV, based on the design of the steel production Taurus sedan

The general target in the design of automotive components and structures is to achieve the required structural performance at the minimum weight. This consideration is often valid also for lightweight design in aluminium since minimum weight reduces the amount of material used and hence the material cost. However, depending on the envisaged production volume and the specified aluminium product form (sheet, extrusion, casting, etc.), there may be deviations from this principle.

The majority of the automotive components and all vehicle structures can be regarded as assemblies of three types of elements, namely:

- thin walled beams,
- panels and
- solid beams or profiles.

The performance of aluminium in these types of application elements depends on the yield strength of the applied alloy and three more or less invariant material parameters, namely its elastic or Young's modulus (70x10^3 MPa), the Poisson's ratio (0.33), and the density (2.7x10^3 kg/m^3).

The consequences of these material parameters on the weight reduction potential of aluminium substituting steel vary depend on the type of the structural element, and on the relevant structural design criterion:

- For a closed thin walled beam (tube or rectangular hollow profile) and constrained outer dimensions where stiffness (bending and torsion) is critical, no weight can be saved in comparison with steel and the yield strength is not a factor.
- However, in solid beams, profiles or open tubes under torsion load and constrained outer dimensions, approximately 40% weight can be saved.
- For a closed thin walled beam (tube or rectangular hollow profile) under bending or torsion load, up to 50% weight reduction is possible if the package can be changed (i.e. increased).
- When buckling stability is the criterion, then equal performance to steel will be obtained at a wall thickness increase of 1.44 and the weight saving will be 50%.

For panels in bending, yield strength is important and weight saving of up to ~ 50% compared with steel is possible.
2.2.2 Stiffness and elastic energy absorption

Aluminium also has a particular advantage over steel for body structure protection in crash situations. Its lower modulus allows for greater elastic deflection and higher energy absorption at weight savings of up to 64%. Even when the beam is designed to match the steel stiffness, energy absorption is higher and 40-50% weight is saved. Some examples are outlined below:

a) Case 1:
Consider a steel beam and an aluminium beam of equal cross section, material yield strength and bending moment when plastic bending occurs are equal:

- The weight saving is 64%, however, the stiffness is only one third.
- Displacement before yield, and hence the elastic energy absorbed, is three times that of steel.

Equal material yield strength and cross section means consequently equal yield load:

b) Case 2:
Consider a steel beam and an aluminium beam under bending load where the material yield strength is equal, but where the wall thickness of the aluminium beam is varied:
THE Aluminium Automotive MANUAL

- Stiffness of the aluminium beam more than one third of the steel beam
- Maximum elastic displacement is more than three times that of the steel beam
- Elastic energy absorbed is more than three times higher
- Weight saved: 64%, however, stiffness is still lower than for the steel beam.

Material yield strength is equal, but as the wall thickness of the aluminium beam is increased with respect to the bending load:

c) Case 3:

Consider a steel beam and an aluminium beam under torsion load where the material yield strength is equal, but where the wall geometry of the aluminium is optimized with respect to torsion loading:

- Stiffness of the aluminium beam more than one third of the steel beam
- Maximum elastic displacement is more than three times that of the steel beam
- Elastic energy absorbed is more than three times higher
- Weight saved: 64%, however, stiffness is still lower than for the steel beam.
Material yield strength is equal, but as the wall geometry of the aluminium beam is optimized with respect to the torsion load:

![Graph showing yield strength comparison]

**d) Case 4:**

Consider a steel beam and an aluminium beam where the material yield strength is equal, however, the cross section of the aluminium beam is increased to achieve the same stiffness as that of the steel beam:

- Maximum elastic displacement is approximately 2.5 times that of the steel beam
- Elastic energy absorbed is more than six times higher
- Weight saved: 40 – 50 %

Material yield strength is equal, but as the cross section of the aluminium beam is adjusted to make beam stiffness equal:

![Graph showing stiffness comparison]

Version 2011 © European Aluminium Association (auto@eaa.be)
The last two cases consider the application of a higher strength steel grade, i.e. the material yield strength and the bending moment when plastic bending occurs are for steel twice that of aluminium.

e) Case 5:

Consider the stiffness of a steel beam and an aluminium beam of equal cross section:

- The weight saving is 64%, however, the stiffness of the aluminium beam is only one third of that of the steel beam.
- Displacement before yield, and hence the elastic energy absorbed, is for the higher strength steel is one third higher than that of the aluminium beam.

Yield strength of steel is twice that of aluminium:
f) Case 6:

Consider a steel beam and an aluminium beam where the cross section of the aluminium beam is increased to achieve the same stiffness as that of the beam made from a high strength steel grade:

- Equal stiffness, but material yield strength of steel is twice that of aluminium,
- Displacement of the aluminium beam somewhat more than that of the steel beam
- Elastic energy absorbed by the aluminium is higher
- Weight saved: 40 – 50 %

Aluminium cross section is increased to get equal beam stiffness to the steel beam:
2.3 Assembly methods and tolerances

As noted in the introduction to the chapter "Design Philosophy", thought must be given to the applied assembly system already at the time when the aluminium component is designed and the various product forms are selected. Otherwise, a plurality of different joining systems may be required, potentially adding to both capital and operating costs. Furthermore, also the quality of the final product might be significantly affected. The applied joining method determines for example critical characteristics of the structural assembly such as its stiffness, fatigue strength or crash performance.

As an example, it is possible to significantly enhance the structural stiffness of an assembled structure by the introduction of stiff and/or continuous joints.

Finite element model of vehicle frame showing stiffness benefit of using stiff joints instead of conventional joints

The intended manufacturing volume, the existing assembly facilities (equipment, lay-out, etc.) and the skill base of the work force must also be considered. The production of a fusion welded aluminium structure in a facility where the experience base is the spot welding of stamped steel sheet components, might not be a good fit. In this case, the development of a new or restructured facility could be a better option.

But even if a joining method which is well established for steel such as for example resistance spot welding is used for aluminium, there are significant differences. In order to achieve an optimum result, it is necessary to have the appropriate equipment and to apply suitable processing parameters. Most important, specifically trained operators are required.
2.3.1 Joining techniques

Aluminium components can be joined among themselves and with other materials with the help of numerous methods. The selection of an adequate joining technique depends on the material combination to be joined, the required joint characteristics, the boundary conditions given by design & engineering as well as production engineering and, last but not least, economic considerations. A critical point is for example the accessibility of the joint location. Many joining methods ask for double sided access. Limited access to the location of the planned joint (single sided or constrained double sided access) will drastically restrict the range of the applicable joining techniques and may require specific preparation steps (e.g. pre-drilled holes).

In principle, the assembly methods used for aluminium alloys do not differ much from the techniques applied for components made from bare and/or coated steels as well as cast iron. It must be noted that in a specific case, however, the best suited methods are not necessarily identical for the two materials, both from a quality and a cost point of view. In addition, an adaptation of the process parameters to the intrinsic characteristics of the aluminium alloys is generally indispensable. The most important joining technologies used for the assembly of aluminium car bodies are briefly characterized below. In special applications, also other joining processes may be used which are not covered here (for example brazing and soldering, rotary friction welding or ultrasonic welding). This qualification applies in particular to mixed material designs, for example to the assembly of aluminium with other metals (steel, magnesium, ...) or plastics and composites.

The application of resistance spot welding, the standard steel joining technique, is possible for aluminium. Reliable and safe resistance weld spots can be produced using suitable equipment and joining procedures. As a consequence of the higher heat conductivity and the lower electrical resistance of aluminium compared to steel, an up to three times higher amperage and about three times longer welding times are necessary to produce an aluminium spot weld. Furthermore, in order to avoid the formation of notches during resistance spot welding, the active surface of the electrode is usually increased, i.e. stronger welding tongs are required. It should be also noted that the electrodes deteriorate much faster than when welding steel and have to be polished or replaced sooner to avoid surface damage. For these reasons and because of the need for more intricate current supply and control equipment, resistance spot welding is seldom applied for joining aluminium components.

Volvo GWT500 scissor type spot welding gun, which provides stiff arms for long reach situations

For the assembly of hang-on parts, flanging or hemming is generally used to join the inner and outer panels, often combined with flange bonding. The flat fold can be usually realised without any difficulty. Aluminium alloy sheets optimised for outer body application also allow the realization of a flat fold with a sharp edge to satisfy higher requirements on the visual appearance of the gap between two adjoining panels. In addition, technologies like friction
spot welding, laser spot welding and mechanical joining methods like clinching or self-piercing riveting are applied in the assembly of closure parts. In some cases, adhesive bonding is also combined with these technologies (leading in general to punctiform joints) to improve the stiffness of closure parts like hoods or doors.

The application of the clinching process (with or without cutting) is generally limited to non-structural applications. Clinching without cutting of the sheet permits the production of more or less tight joints. But these joints exhibit inferior mechanical characteristics when coated or lubricated sheets are joined. On the other hand, clinching with a cutting element clearly improves the mechanical characteristics of the joint.

Other mechanical joining processes, however, are well suited for the assembly of aluminium body structures since the joint is produced without any thermal impact. Mechanical joining methods also offer the possibility to join coated materials as well as combinations of different materials. In addition, they enable the introduction of functional elements such as nuts or bolts into a sheet metal component. The disadvantage is a local change of the surface geometry. Thus, mechanical joints are visible and, depending on the applied method, there may be a slight deformation in the vicinity of the joint.

In the assembly of aluminium car body structures and mixed aluminium-steel structures, mechanical joining methods like riveting, screwing or bolting are commonly used with excellent results, very often combined with structural adhesive bonding. In particular self-piercing riveting offers a very good cost-benefit ratio. Special versions of these process also allow joining with one-sided accessibility.

The mechanical strength and, in particular, the fatigue strength of the resulting joints is generally very good. The actual mechanical characteristics depend on the joint geometry, the applied joining method, the type of the joining element (material, geometry), the joining conditions and the characteristics of the partner materials. Close attention must be paid to avoid the potential occurrence of galvanic corrosion effects. For aluminium or steel-aluminium joints, the joining elements are usually made from steel and equipped with proper corrosion protection (different coating methods are applied) or made from stainless steel. But also aluminium screws are in use.
Most important in the manufacturing of aluminium structures are also the fusion welding processes. Among the conventional arc welding methods, MIG welding with a properly selected filler wire is best suited for aluminium welding. MIG welding is mainly used in the body structure, but newer developments enable also the welding of thinner sheets. However, it must be noted that the weld seam as well as the heat-affected zone exhibit inferior mechanical characteristics than the base material. In order to minimise these effects, to avoid geometrical distortions of the welded assembly and to reduce internal residual stresses, it is important to keep the heat energy input at a minimum level. Thus fusion welding methods with local melting by means of focused high-energy laser or electron beams find more and more interest. Laser welding with either Nd-YAG or diode lasers is highly flexible and particularly suited for aluminium. Laser welding allows the execution of high quality joints at relatively high speeds, it is well adapted for joining thinner gauge material and can be used to produce either continuous, narrow weld seams or single punctiform joints. In specific cases, aluminium sheets, profiles or castings are also joined by hybrid technologies such as Laser-MIG welding.

Automated MIG welding of a sub-frame for the BMW 5-series vehicle

Source: Hydro Aluminium Rolled Products

Today, adhesively bonded joints are increasingly used in the body assembly plant. Adhesive bonding offers a range of potential advantages:

- High rigidity of the joint
- Good dimensional accuracy of the design
- Excellent performance under fatigue loading
- Noise and vibration dampening capability
- Additional corrosion protection
- Blemish-free surface appearance
- Possibility to join different materials

In car body design, the applications of adhesive bonding include not only fairly uncritical cases such as hem flange bonding or the fixation of linings, but also the realisation of safety-critical structural joints. Depending on the specific requirements, different adhesive qualities are offered by the suppliers. The selection criteria for the adhesive are given by design and manufacturing considerations. In particular for structural applications, an appropriate preparation of the aluminium sheet surface is most important in order to guarantee the long-term stability of the adhesively bonded joint.

In case of structurally loaded joints, adhesive bonding is generally combined with another joining technology, for example resistance spot welding and/or mechanical joining (clinchling, self-piercing riveting, screwing, etc.). The advantages of these hybrid joining methods compared to pure adhesive bonding are:

- Mechanical fixation of the adhesive joint until the adhesive hardens either by a specific hardening treatment or in a subsequent thermal treatment (in general the lacquer bake hardening step).
- Improved performance of the adhesive bond under peeling loads: If the peel strength of the adhesive is exceeded, the load can be supported up to a certain amount by the locally fixed mechanical connections.
2.3.2 Assembly process

The construction design and the joining method (or methods) dictate the assembly sequence and the type of the required assembly jigs. Again, this must be thought through already at the commencement of the design process so that the employed product quality, the design of the components and the part configuration can be optimised for the adopted assembly system. For example, if fusion welding is selected and aluminium castings are involved, the cast parts must be produced by a process where they are readily weldable without the development of excessive weld porosity. In particular for extruded and cast aluminium components, the possibility to integrate joining flanges may also offer significant benefits in the assembly process. The selected joining method determines the size, location and configuration of joining flanges or overlaps. Another important point may be the preparation of the required surface quality of the aluminium component.

The envisaged production volume will determine if manual or automated joining processes are appropriate. An important parameter limiting the selection of the applicable joining technique is the accessibility, in particular when robots are used. The actual choice of the applied joining technique is both a technical and economical decision. The basic requirement is that the chosen joining technique (continuous or discontinuous, type and location of joints, etc.) fulfils all the technical demands at the lowest cost (investment and operating cost).

Proper care must also been taken in the planning of the handling and fixation systems. The soft aluminium surface requires specific attention and, in particular, any surface contamination (dirt, metallic fines, etc.) must be avoided. This is most important for outer body panels. The aluminium sheet surface is softer and more sensitive to scratches, dents, etc., than the steel sheet surface. Today, aluminium car body sheets are generally supplied coated with oil or, preferentially, with a dry lubricant. Thereby both an appropriate corrosion protection and protection against handling and transport damage are achieved.

Assembly of the aluminium floor structure of the Jaguar XK

Source: Jaguar
2.3.3 Sources of tolerances

The selected joining method determines the size, location and configuration of joining flanges or overlaps and the precision of edge trim required. This in turn impacts on the choice of the part manufacturing process as well as the acceptable tolerances.

The precision by which the separate parts of an assembly come together has a critical impact on joining. Thus appropriate part shape tolerances must be maintained to avoid making poor or unsound joints.

The problem is of particular concern in large assemblies as shape and tolerance errors build-up and significant force may be needed to bring final parts together for joining. This is another reason why every opportunity should be taken to reduce the part count by part integration.

Parts which are cold formed (stamped sheet components, bent extrusion, etc.) generally present the biggest problem in regards to tolerances. This is due to springback and is larger for aluminium than steel due to its lower elastic modulus. Distortion problems may result also when cast aluminium components are subjected to a heat treatment involving a quench.

All-aluminium Audi A8, assembly of the doors

Source: Audi
2.4 Material selection criteria

While a wide range of aluminium alloys are produced by the aluminium industry, not all are suitable for automotive applications. The industry has therefore developed certain aluminium materials especially for automotive use, using its experience in working with the auto industry to determine the final product requirements and then to optimize the required material properties and characteristics. Thus, the normal material of choice should be one of those specifically developed for automotive applications. This ensures availability and production to the quality and tolerances required for automotive production.

The specific alloy compositions and heat treatments differ somewhat for sheet and extrusion applications and more so for castings.

In the following sections a brief outline of the preferred material types for each of these product forms will be presented. For details please check the dedicated chapters of the Automotive Aluminium Manual.
2.4.1 Automotive sheet products

Essentially two types of automotive sheet materials have been developed. These are the medium strength highly formable AA 5xxx Al-Mg alloys for structural applications, and the AA 6xxx Al-Mg-Si heat treatable alloys for higher strength and surface critical applications. The AA 6xxx alloy sheets are the standard materials for outer body applications since the appearance of surface inhomogeneities during forming can be avoided. In contrast, AlMg alloys tend to form stretcher strain markings during forming which appear either as large, flamy patterns (Lüders lines of type A) or very fine striations (Lüders lines of type B).

Copper-free AlMgSi alloys of the type AA6016 or variants as well as higher strength AlMgSi materials with small copper additions such as AA6111 dominate the closures market. With close control of the concentration of the alloying elements, a selected Mg/Si ratio and specially adapted processing conditions, these alloys fulfill high formability requirements (in particular also with respect to bendability) and high strength.

All Al-Mg-Si alloys are supplied in the highly formable T4 temper, but strengthen significantly through the combination of forming and subsequent paint baking and thus provide excellent dent resistance, even at thicknesses close to those for comparable steel applications. The small copper content of AA6111 has in practice never led to any corrosion problems.

For inner and structural applications, both AlMg and AlMgSi alloys are applied. The long established AlMg alloys (e.g. AA5754, AA5182, etc.) are characterized by a very good formability which enables the production of parts with complex geometrical shapes and guarantees in case of a crash a good energy absorption capacity and prevents early failure of the component by brittle fracture. For applications where exposure to heat and a corrosive environment will be encountered, however, the Mg should be limited to 3% as alloys with a higher Mg content can develop sensitivity to stress corrosion after extended exposure to elevated temperatures.

The Al-Mg alloys are most frequently supplied in the fully annealed O temper to provide optimum formability. This strength level should be the basis for design and dimensions, even though these materials work-harden on forming. They are thermally very stable, have excellent corrosion resistance, are readily weldable and remain ductile, even after forming.

The AA 6xxx materials are not as readily weldable as the AA 5xxx alloys and can continue to strengthen and lose ductility with long term thermal exposure at high temperatures (>160 - 180°C). However, if the appropriate precautions are followed, there are many structural applications where the high strength can be used with advantage to save weight and space.
If alloys of the same alloy family are used for both inner and outer panels, the recycling of the inherent process scrap in the press plant is clearly simplified. This is also valid for the recycling of aluminium hang-on parts dismantled from end-of-life vehicles. For this reason the use of AlMg sheet materials is more and more limited to non-visible structural components of the car body where highest formability is required either during production or in the service phase of the car.

but where very deep inners are required, the higher formability Al-4.5Mg alloy can be used with advantage.

The liftgate shown on the right illustrates such an application. The outer panel is made from the AA 6111 alloy which ensures the necessary dent resistance at minimum sheet thickness whereas the very deep inner panel consists of a highly formable Al4.5Mg alloy (AA 5182).

Various other aluminium sheet materials have been developed for more specialized applications, notably bare and clad materials as sheet, tube and fin stock based on the 1xxx, 3xxx and 7xxx series alloys for brazing applications for heat exchangers. For details please see the appropriate sections of this manual.
2.4.2 Automotive extrusions

The extrusion process for producing aluminium shapes and profiles gives aluminium a unique advantage over steel. Extruded profiles are two-dimensional design elements with the advantage that there are little design limitations with respect to the complexity of the cross section (varying wall thicknesses, multi-chamber profiles, addition of flanges, etc.). Subsequent forming (bending, stretch forming, hydroforming) and machining processes also allow for limited three-dimensional design capability. These possibilities can be fully exploited in the car body structure. Very complex sections with internal webs and external flanges can be produced at wall thicknesses that allow minimum section weights to be achieved for the structural function of components. Tooling costs are small compared with sheet stamping.

The commonly used extrusion alloys are based on the heat treatable AA 6xxx alloy series offering a wide range of strength, both in the T4 temper and after heat treatment to T5 or T6 tempers. Some heat treatable AA 7xxx alloys are also used for structural applications, mainly for crash performance.

Extrusions can be shaped by bending or in the T4 temper, pierced and/or machined to modify flanges, and used in this state or after aging. Most joining methods are suitable, with fusion welding being the favoured process. With smaller structures, artificial ageing to the T6 temper can follow welding and shape rectification.

For aluminium profiles, the strength requirements are very often not the limiting factor as the minimum wall thickness is mainly determined by the manufacturability of the profile ("extrudability"). From a metallurgical point of view, a finely recrystallized microstructure is generally strived for good formability (bending, hydroforming) and weldability. Table 5 lists some extrusion alloys which are today used in the car body structure.
Chemical composition of selected extrusion alloys for the car body structure

Most important is also the applied temper. In the T4 temper which is produced by rapid quenching immediately after extrusion, formability is highest. However, for improved strength, extruded car components are generally heat treated after forming. Highest strength is achieved in the T6 temper (fully age hardened) whereas for optimum crash performance, the formed components are annealed to an overaged temper T7.

True stress-strain curves for AA 6014 in different tempers; proper selection of the annealing conditions assures optimum performance
2.4.3 Automotive castings

Castings are particularly suitable when complex shaped components are needed and the tooling and joining costs for producing an equivalent component from sheet stampings would cost more. Other components such as cylinder blocks and heads, transmission housings, oil pans, etc., can only be produced by casting and here aluminium offers significant weight saving over cast iron. This is true for wheels and other applications where the design freedom offered by casting processes is the primary selection criteria.

As more sophisticated high quality casting processes and control procedures that provide higher structural integrity become available, castings can also be considered for suspension parts, chassis and structural body components.

Most casting alloys are based on the Al-Si alloy system. Many casting alloys, in particular for non-structural applications, are produced from recycled aluminium. However, for safety-critical and structural application, in general casting alloys based on primary aluminium (i.e. with low iron content) are used. Commonly used for structural parts are the alloys Al-7%Si (A356), Al-10%Si-0.3%Mg and Al-5%Mg-2%Si.

There is a wide range of casting processes, with each having particular merits for certain types of parts. Equipment cost, tooling cost and lifetime, and production volume also determine what the preferred or most economical process is.

The casting shown below has been converted from a stamped steel sheet assembly and is just another example of the part and function integration that can be achieved with aluminium castings.

Vacuum high pressure die casting is often applied for the production of thin-walled structural components. Apart from the availability of a top quality pressure die casting process, the decisive factors for the successful application of such structural die castings are the correct choice of the alloy composition and the applied heat treatment. A critical aspect is the die-filling capability necessary to produce the thin-walled parts showing
complex shapes with large surface areas. These requirements are met by the alloys of the Al-10%Si-0.3%Mg type with the silicon level close to the eutectic point in order to achieve the required fluidity. Compared with the usual pressure die casting alloys, these type of alloys contain less iron which was largely replaced by manganese to prevent extensive die sticking. The selected Mn/Fe ratio results in a fine and uniform dispersion of the quaternary AlFeMnSi phase and prevents the forming of brittle needles of the AlFeSi phase.

B pillar of the Audi A2; vacuum high pressure die casting (left) and final component (right)

Source: Alcan

AlSi casting alloys have to be heat treated at high temperatures to allow the globularization of the eutectic silicon and thus ensure high ductility and good crashworthiness. The usual practice of annealing at about 500°C with rapid quenching in water to room temperature would lead to heavy distortion of the thin-walled parts. Therefore, it was necessary to develop a special partial solution heat treatment with subsequent air-quenching to keep the distortion within acceptable limits.

Alternatively, casting alloys of the type Al-5%Mg-2%Si, which do not need a heat treatment, have been developed to avoid any distortion issues.

Rear cross member, a vacuum high pressure die casting made from the alloy Magsimal-59 (Al-5%Mg-2%Si)

Source: Aluminium Rheinfelden
2.5  **Examples of potential weight savings**

2.5.1  **Design for equivalent strength**

Where a tensile or compressive stress occurs with no risk of buckling, it must be verified that the permitted stresses are identical:

\[
\frac{Y_S}{S_{\text{steel}}} \times S_{\text{steel}} = \frac{Y_S}{S_{\text{alu}}} \times S_{\text{alu}}
\]

\[
S_{\text{alu}} = S_{\text{steel}} \times \frac{Y_S}{S_{\text{alu}}}
\]

where:
- \(Y_S\) = yield stress of the part made from aluminium
- \(Y_S\) = yield stress of the part made from steel
- \(S_{\text{steel}}\) = area of the steel section
- \(S_{\text{alu}}\) = area of the aluminium alloy section.

The yield stress (YS) is equivalent to \(R_{p0.2}\).

Depending on the steel grade and the aluminium alloy/temper considered in such a comparison, aluminium can save up to 80% in weight (when comparing for example mild steel and an age hardened aluminium extrusion).

For bending stress, it must be checked that the permitted moments are identical:

\[
\frac{Y_S}{I/\nu_{\text{steel}}} \times I/\nu_{\text{steel}} = \frac{Y_S}{I/\nu_{\text{alu}}} \times I/\nu_{\text{alu}}
\]

\[
I/\nu_{\text{alu}} = I/\nu_{\text{steel}} \times \frac{YS_{\text{steel}}}{YS_{\text{alu}}}
\]

where:
- \(I/\nu_{\text{steel}}\) = flexure modulus of the steel section
- \(I/\nu_{\text{alu}}\) = flexure modulus of the aluminium alloy section.

When the deformation of the structure is not a determining design factor, the use of a shape made from an aluminium alloy such as AA6005A in the T5 temper (which may show the same proof stress as many steel grades) could result in a 66% weight saving.

Considering the special case of a sheet under bending stress: Based on the strength criterion, replacing a deep drawing quality steel sheet for which \(Y_S\) is of the order of 180 MPa by an aluminium sheet in AA6016 (\(Y_S>200\) MPa after forming and lacquer bake hardening) or AA5182 (\(Y_S>135\) MPa) results in a weight savings of well over 50%:

\[
Y_S \times t_{\text{alu}} = Y_S \times t_{\text{alu}}^2
\]

\[
t_{\text{alu}} = t_{\text{steel}} \sqrt{\frac{YS_{\text{steel}}}{YS_{\text{alu}}}}
\]

where \(t\) = sheet thickness.
2.5.2 Design for equivalent stiffness

For a uniform tensile or compressive stress, it must be checked that the permitted stresses are identical:

\[ \frac{E_{\text{steel}}}{E_{\text{alu}}} = \frac{S_{\text{steel}}}{S_{\text{alu}}} \]

\[ S_{\text{alu}} = 3 \times S_{\text{steel}} \]

This is the worst case when looking for the theoretical weight saving potential. In this case, substitution of steel by aluminium will not lead to any weight saving. In practice, however, this case where a component requires simultaneously tensile strength and stiffness, occurs very rarely.

For the most common case of a bending stress, it must be checked that the permitted moments are identical:

\[ \frac{E_{\text{steel}}}{E_{\text{alu}}} = \frac{I_{\text{steel}}}{I_{\text{alu}}} \]

\[ I_{\text{alu}} = 3 \times I_{\text{steel}} \]

Inertia must be balanced by increasing the height of sections and by positioning the masses away from the centre of gravity. An intelligent design that uses castings or extrusions will save in this case 25% to 30% on weight.

Notations:

- \( E_{\text{alu}} \) = Young's modulus for aluminium
- \( E_{\text{steel}} \) = Young's modulus for steel
- \( S_{\text{steel}} \) = area of the steel section
- \( S_{\text{alu}} \) = area of the aluminium alloy section
- \( I_{\text{steel}} \) = inertia of the steel section
- \( I_{\text{alu}} \) = inertia of the aluminium alloy section
2.5.3 Design for equivalent stiffness – Sheet

![Renault Laguna, hood inner panel](Image)

Source: Constellium

In the particular case of sheets under a local bending load (closures and body structure), the sheet thickness must be increased by a factor of 1.45. The resulting weight saving is 50%. There is no influence of the involved aluminium alloy or steel grade. In the following example, the 0.7 mm thick steel sheet is replaced by a 1 mm thick aluminium sheet. In order to meet the requirement for limited strain, it must be ensured that:

\[
\frac{t_{\text{alu}}}{t_{\text{steel}}} = 3 \sqrt{\frac{E_{\text{alu}}}{E_{\text{steel}}}} = 1.44
\]

with the result:

\[
\frac{\text{mass}_{\text{alu}}}{\text{mass}_{\text{steel}}} = 1.44 \cdot \frac{\text{density}_{\text{alu}}}{\text{density}_{\text{steel}}} = 1.44 \cdot \frac{2.7}{7.8} = 0.5
\]

In closure applications, a most important design criterion is the dent resistance. The resistance offered by an external car body panel to the impact by a projectile constitutes a major design limitation. A panel's impact resistance depends on a number of factors:

- the properties of the material (modulus, proof stress, density)
- the loading conditions (projectile velocity),
- the panel's stiffness which in turn is determined by its geometry (gauge, length, width, curvature radii).

![Renault Laguna, hood outer panel](Image)

Source: Constellium

a) Static dent resistance

Given the respective proof stresses of the two materials in a finished part, the aluminium sheet gauge required for an equivalent static dent resistance as that of steel is given by bending considerations:
where:
\( t = \text{sheet thickness} \)
\( \text{YS} = \text{yield stress} \).

In many cases, a sheet thickness ratio of 1.45 can be reached between the two materials, i.e. a 50 % weight saving is possible.

b) Dynamic dent resistance

The dynamic dent resistance depends on specific test conditions due to the different effect of the test dynamics on the yield stress of aluminium and steel as well as, in some cases, inertia effects resulting from the design of the component. As a rule, the yield stress of steel increases more quickly than that of aluminium when the impact speed increases.

For 50 % weight saving (i.e. 0.7 mm steel versus 1 mm aluminium gauge) and equivalent dynamic dent resistance on a flat part such as found on a bonnet, the following graph indicates that a aluminium panel with a yield stress of 180-200 MPa can replace a steel panel with a yield stress of 350-400 MPa.

![Aluminium equivalent panel versus steel reference, graph based on dynamic dent studies](image)

c) Example: Hood design

Peugeot 307, hood inner panel

Source: Constellium
The stiffness and dent resistance of a steel hood can be matched with an aluminium hood with a 50% weight saving. For mild steel, down gauging is limited by the dent resistance. For higher strength steel grades, down gauging is limited by the stiffness.

<table>
<thead>
<tr>
<th>Design criteria</th>
<th>Specification</th>
<th>Mild steel (YS = 200 MPa)</th>
<th>High strength steel (YS = 300 MPa)</th>
<th>Alu 6016 (YS = 150 MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dent resistance</td>
<td>YS × t ≥ Cte</td>
<td>t ≥ 0.8</td>
<td>t ≥ 0.65</td>
<td>t ≥ 0.92</td>
</tr>
<tr>
<td>Local stiffness</td>
<td>E × t^2 ≥ Cto</td>
<td>t ≥ 0.7</td>
<td>t ≥ 0.7</td>
<td>t ≥ 1</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td></td>
<td>14</td>
<td>12.4</td>
<td>6.1</td>
</tr>
</tbody>
</table>

*) after deformation and paint baking

The table shown above takes a very conservative approach. In reality, in aluminium hoods using alloys of the type AA6016, the strength level reaches values well over 200 MPa after forming and lacquer bake hardening.