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REVIEW

Application of Aluminum and ITS Alloys in the Automotive Industry With Special Emphasis PN Wheel Rims

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Abstract: The use of aluminum in modern cars began in the early 1970s, when under the pressure of the oil crisis, car manufacturers around the world began to reduce the weight of cars in order to achieve the lowest possible fuel consumption. The first applications of larger volumes were radiators, engine blocks and wheels. Meanwhile, in Europe, the average amount of consumed aluminum has continued to increase, reaching an average of 180 kg per car. Aluminum castings, forgings, sheets and extruded parts are used for a large number of car parts, including car bodies, chassis, suspensions, wheels and many others. The use of aluminum is also important for hybrid and battery electric cars. Due to the threat of global warming due to the greenhouse effect, it is very important to reduce the weight of the car by using aluminum, and thus fuel consumption.This paper explains why, now more than ever, vehicle weight reduction is necessary and how aluminum can be used to further improve the sustainability and safety of future generations of cars. Special attention is given to the use of aluminum for car wheels, which represent almost 15% of the average aluminum content in passenger cars.

Key words: Aluminum alloys, light metals, steels, automotive industry, wheel rims..

INTRODUCTION

Metals are still the most commonly used materials in the automotive industry. In addition to steel, one of the most important light metals on cars is certainly aluminum, the use of which is becoming more frequent, but still relatively rare.

Probably the most famous aluminum car will forever remain the “Audi A2” (Figure 1), which was expensive and whose poor sales stopped production somewhere in the middle of the planned production cycle. But this car was not expensive in itself, but the high price was primarily due to the technology of making cars from aluminum, which is still more expensive than the one in which we use steel. [1, 2]

Figure 1. Aluminum in the automotive industry, model Audi A2

Lightweight materials such as aluminum and its alloys do not only bring weight savings to the vehicle. The savings in terms of production costs are also significant because this material enables the application of new processing technologies, and thus, in some cases, lower energy consumption. Also, the advantage of materials such as aluminum is the possibility of making car parts with better properties. In addition to new ways of joining aluminum surfaces, one interesting advantage of this metal is the development of special ways of pressing aluminum sheet used to make the hoods, trunk hatches, as well as front and rear bumpers (high speed blow forming). In this process, the aluminum sheet is heated to a temperature of 500 ° C in a heated mold. After the sheet is heated, a medium under high pressure acts on it and shapes the part according to the die. [3]

Application of aluminum and its alloys in the automotive industry

Aluminum provides savings of up to 50% compared to competing materials in many applications. The typical relative and absolute mass of the average savings of the main assemblies of aluminum applications in serial production of cars are given in Fig.2. [4]

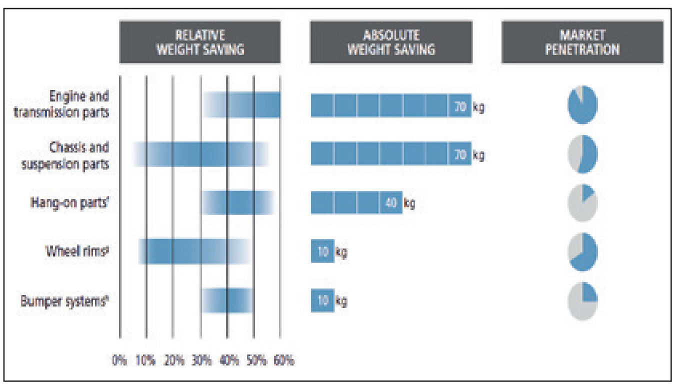


Figure 2. Aluminium's direct weight savings [4]

The Jaguar and Land Rover brands have the highest aluminum content of around 500 kg, and other premium brands are also above market average (149 kg net weight), but many low-budget cars actually contain significant amounts of aluminum as well (Figure 3). [5]

Analyzing European car production (2019) by segment, C-compact class cars (e.g. VW Golf, Ford Focus, BMW i3, etc.) make up the majority of car production (43%) (Figure 4). The segment distribution is projected to remain similar until 2025, but with stronger growth in the B-sub-compact segment (e.g. Audi Q2, etc.) and a reduction in the A-basic segment (e.g. Opel Adam, etc.). [5]

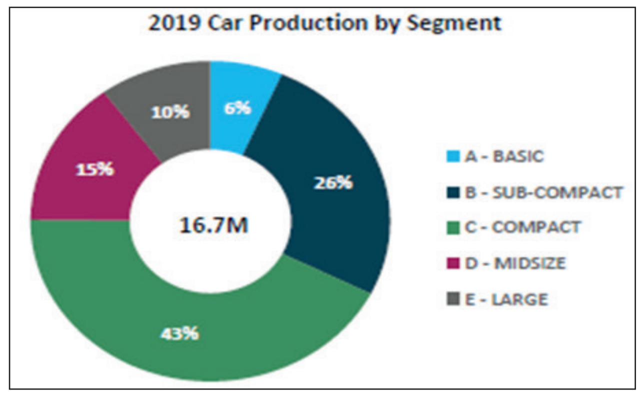


Figure 4. Car production by segment (2019) [5]

Although E-large segment vehicles (e.g. Audi e-tron) have the highest average Al content per vehicle (442 kg) (Figure 5b), C-compact segment vehicles account for the largest share (36%) (Figure 5a) of total Al consumption due to the total production volume of C-compact segment vehicles. [5]

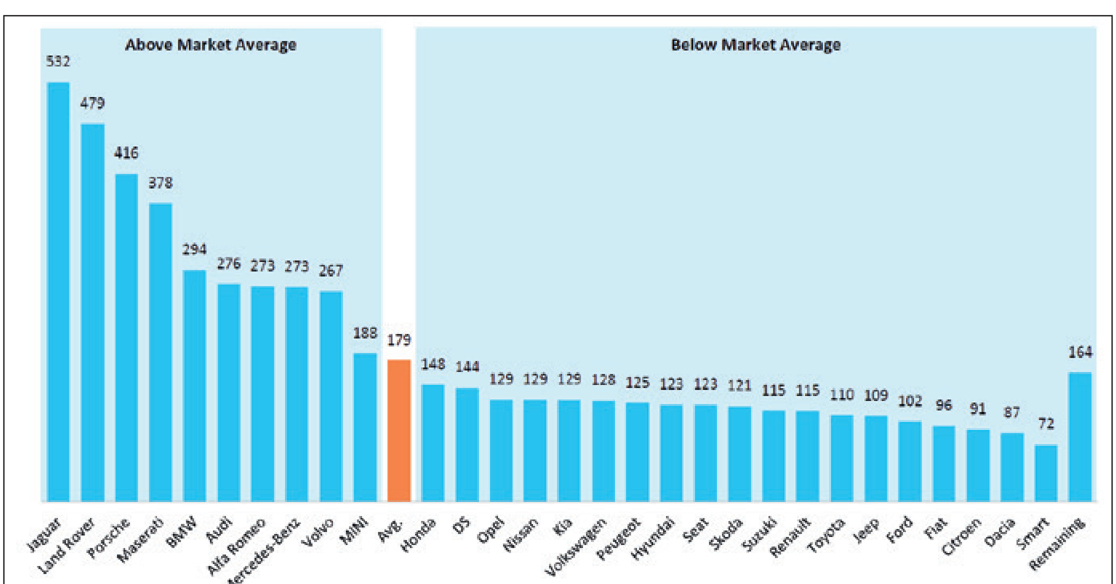
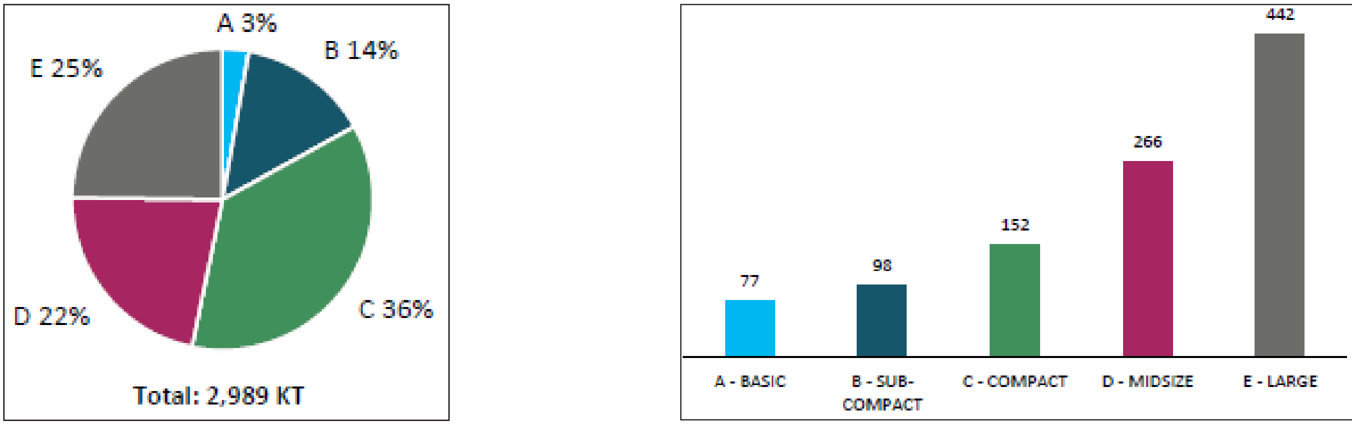


Figure 3. Average Al Content per Vehicle by Brand 2019, (Net Weight in Kg) [5]



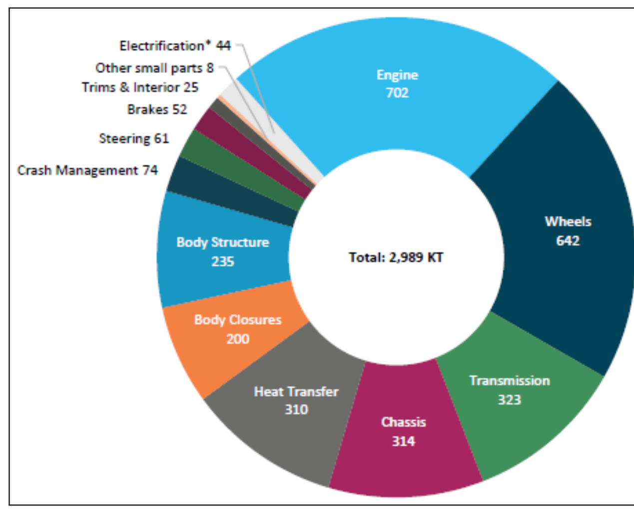
a) b)

Figure 5. a) Total AL Content by Vehicle Segment (2019, Net Weight in %), b) Average AL Content by Vehicle Segment (2019, Net Weight in kg) [5]

The average aluminum content per vehicle in 2019 for European car manufacturers was 179.2 kg. This amount is projected to increase to 198.8 kg by 2025, if small and medium-sized vehicles follow the evolution prediction of the automotive industry. [5]

Analyzing the use of aluminum by component groups in cars, we come to the conclusion that the engine and the wheels represent almost half of the total share of aluminum in the vehicle (~45%) (Figure 6). [5]

Electric vehicles are quite expensive today, mainly due to the cost of batteries. Therefore, it is important to make electric cars as energy efficient as possible. Lightweight aluminum is one way to improve energy efficiency for any vehicle, including ones with the electric propulsion.



Electrification components include Battery Box, Battery Cooling and Electric Motor Housing

Figure 6. Total Aluminum Content by Component Group 2019, Net Weight in KT [5]

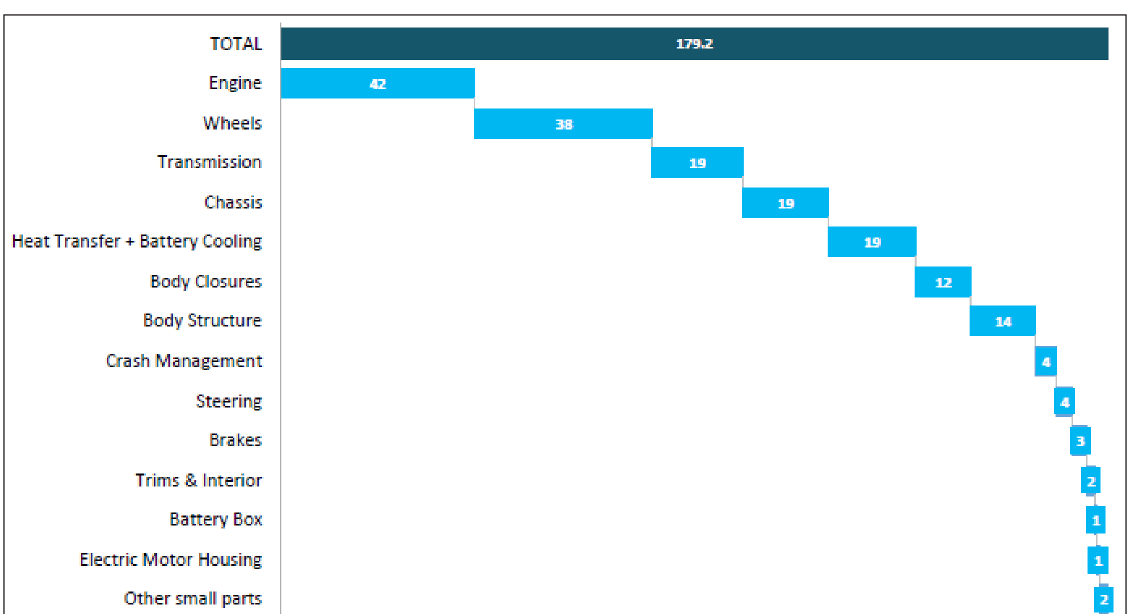


Figure 7. Average Aluminum Content per Vehicle by Component Group Incl. all powertrain types, (Net Weight in kg) (2019 year) [5]

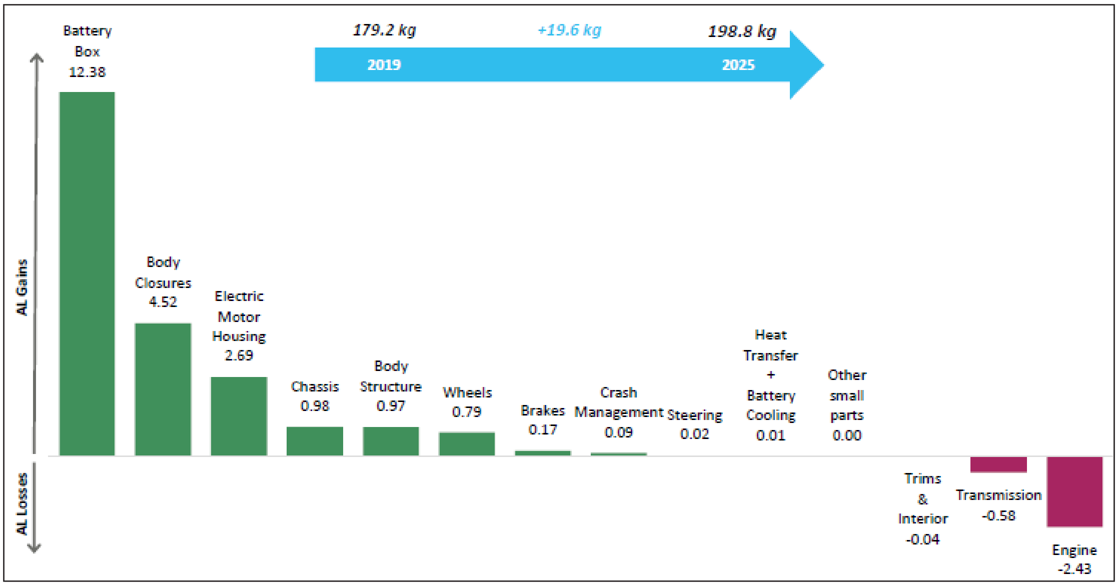


Figure 8. Expected AL Gains & Losses within Average AL Content per Vehicle *For the time period 2019 to 2025 (Net Weight in kg)* [5]

In addition, life cycle analysis of electric vehicles made of steel and aluminum shows that an aluminum electric vehicle during its entire exploitation emits 1.5 tons of carbon dioxide less than steel electric vehicles. [6]

The average aluminum content per vehicle, related to battery boxes and electric motor housings in battery electric vehicles (BEVs) is currently small (Figure 7) but will grow rapidly with the expected growth of electric vehicle production. [5]

According to projections, by 2025, battery boxes and electric motor housings will have the largest contribution within the increase in the average share of aluminum per vehicle (Figure 8). On the other hand, the use of aluminum for traditional engine and transmission components will be reduced. [5]

Nowadays innovative, safe and economical car parts can be found on all car models, regardless of brand and luxury class. For these parts, the transition from steel to aluminum is relatively easy and does not require a complete reengineering of the car. In the car manufacturing practice, material replacement is usually performed during a redesign, which happens seldom for already existing models. The design of parts comprised of mixed materials is generally not a major issue, but it is necessary to solve some problems related to the stiffness of the entire structure, the joining of diverse materials, with different thermal expansion coefficient and the occurrence of electrochemical corrosion. By solving these problems, the potential for weight reduction could be very significant. [1]

Today, high-strength steels (HSS) and advanced-high-strength steels (AHSS) are the dominant materials in the automotive industry. The newly developed AHSS steels of the second generation enable a further increase in the combination of tensile strength and deformation (Figure 9), which makes them suitable for meeting even greater requirements [7]. However, strength is not the only material parameter that should be taken into account when designing a car body. The density and stiffness of aluminum are about one third of the value that steels have, which is very important. By comparing the specific strength (ratio between the strength of the material and its density) between AHSS steel and Al alloys, it shows that aluminum alloys can be competitors to AHSS steels of the first generation6 (Figure 9).

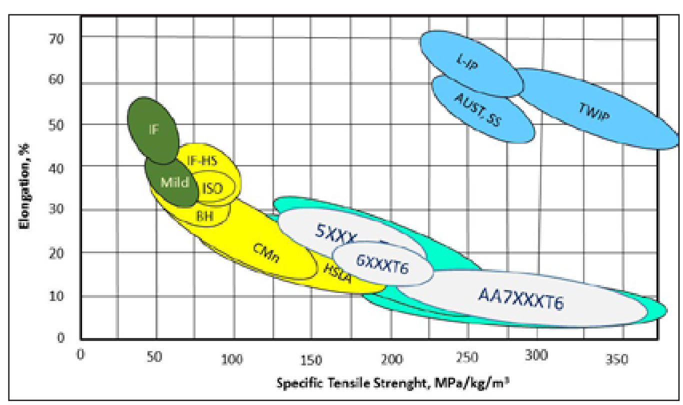


Figure 9. Weight specific comparison of the mechanical properties of aluminium and steels [8]

Aluminum also has a special advantage over steel, it protects the body structure in the case of a collision. Its lower modulus of elasticity allows for greater energy absorption with a weight savings of up to 64%. Even when the beam is designed to match the strength of the steel, energy absorption is higher and 40-50% of weight is saved. [4]

Aluminum alloy parts in the automotive industry can be machined in a variety of ways thanks to the

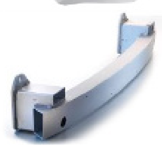
	Average Al Content Per Vehicle	
	Aluminum Content in Cars (2019)	Aluminum Content in Cars (2025)
	179.2 kg	**198.8 kg**
 **Cast**	116.0kg	118.1kg
 **Sheet**	34.0 kg	43.2 kg
 **Extrusions**	19.0 kg	26.7 kg
 **Forged**	10.2 kg	10.7 kg

Figure 10. The average presence of aluminum in cars according to the processing method [5]

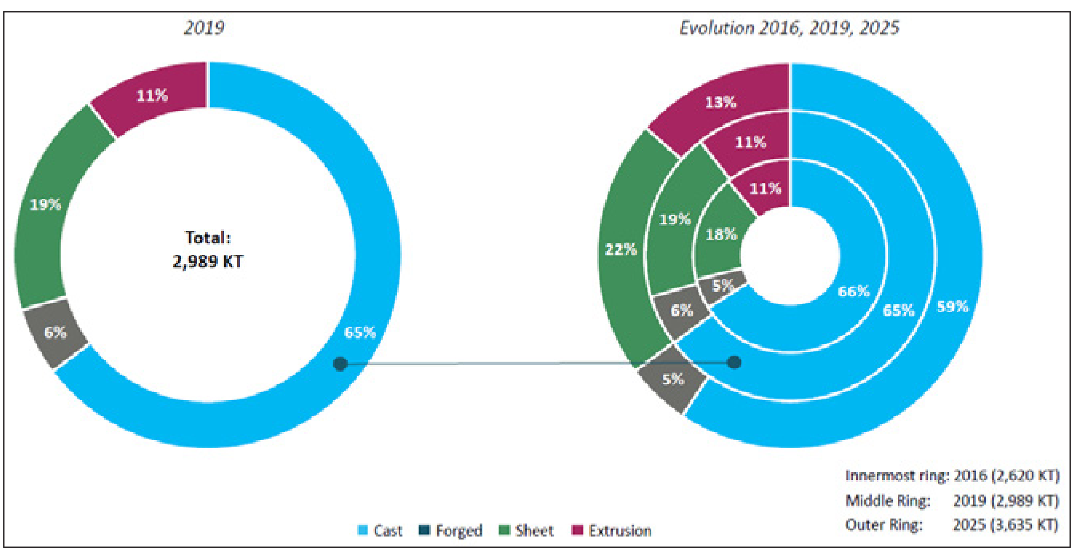


Figure 11. Forming Process Split of Total AL Content (Net Weight in KT) [5]

good machinability of these alloys. The casting process is most often used, followed by pressing sheet metal parts, then shaping parts obtained from extruded profiles, and finally forging, which is the least represented (Figure 10). Thanks to the growing number of electric cars, the trend in the coming period is that the amount of parts obtained by sheet metal processing will increase and that the quantities of parts obtained by casting will decrease (Figure 11).

Today's vehicles must meet an increasing number of strict safety regulations, both in terms of vehicle control and in terms of pedestrian protection. To meet different safety requirements, modern vehicles include a strong and stable passenger space that provides the necessary space to survive in the event of an accident, which is surrounded by a deformation zone in which the impact energy is efficiently absorbed. In the development of car construction, the most important thing is to find an appropriate compromise between construction stiffness, energy absorption capacity in the event of a collision and other requirements. Aluminum is an ideal material of extreme structural stiffness, which is the result of the high thickness of the material (aluminum components are 50% thicker than steel components). [9]

Table 1. Comparison of different types of wheels

Production technology	Steel wheel (sheet, welded)	Cast aluminium (classical)	Cast aluminium (w. hollow spokes)	Aluminium (sheet welded)	Forged aluminium (classical)	Forged aluminium light wheel	Cast magnesium
Weight (relative)	1,0	0,75-0,85	0,7	0,65-0,75	0,60-0,80	0,60-0,75	0,60-0,75
Cost (relative)	1,0	4,5	13,0	3,3	10,0	4,0	16,0

Application of aluminum for car wheel rims

Car wheels consist of tires and wheel rims, however, in the rest of the paper, in order to have concise text, we will use term "wheel" instead of "wheel rim". High quality wheels need to meet all the requirements of standard driving conditions. The most important features expected from the wheels are flexibility and aesthetic appearance, even after long-term use. Another important factor is reduced weight and low moment of inertia. Reducing the total weight of the vehicle also affects the reduction of fuel consumption. In addition, better thermal conductivity of the wheel rim material leads to faster heat dissipation from the brakes, which improves braking in very demanding driving conditions and reduces the chance of brake failure due to overheating. [10]

Various materials can be used to make car wheels: soft low-carbon steels, high-strength steels, aluminum alloys, magnesium alloys, titanium alloys and carbon fiber-reinforced epoxy matrix composite materials. [11]

Steel wheels are often comprised of multiple pieces of pressed sheet metal welded together. They are less likely to consist of single piece due to complicated production. They are still found on many cars today because they are cheap, durable and flexible, but on a down side, they are also heavy. Instead of low-carbon steels for wheels, it is possible to use high-strength steels (HSS) which, with the same strength as low-carbon steels, have a lower weight. [12]

Magnesium alloy wheels are much lighter compared to other materials and have very good mechanical properties, both static and dynamic. Poor resistance to atmospheric influences is overcome by alloying and appropriate coatings. Mg alloy wheels are expensive so they are mainly used for race cars and luxury class cars. [13]

Titanium is a material that is very resistant to corrosion and has a strength that is 2.5 times greater than the strength of aluminum. However, the cost of production is very high, moreover, it is not available for commercial car classes. Titanium wheels are still in the early stages of development for road cars, but are sporadically used for racing and luxury cars. Poor wear resistance is eliminated by nitriding the surface layer or applying other hard coatings. [14]

Composite materials with polymer matrix and carbon fiber as reinforcement represent the latest group of materials that is trying to find its application for car wheels. This group of materials is much lighter than other materials used for vehicle wheels and the first tests showed very good dynamic resistance. [15]

The appearance of the wheels made of different materials is shown in the Figure 12.

A comparison of different types of wheels, made of different types of materials and different technologies, both in terms of relative weight and relative price in relation to the steel wheel is given in the table 1. [16]

Aluminum alloys used for the production of wheels have a significant role in the automotive industry, initially found in the luxury and sports models, today they are an option in the middle and lower class cars as well. On the market, wheels made by casting from Al-Si type alloys are the most common. In an effort to achieve the lowest possible wheel mass, molding technology has been developed, as well as wheel fabrication by sheet metal extrusion and spinning forming.

The successful start of aluminum wheel production in Europe began with the development of the 1962 Porsche 911. Porsche was looking for a special wheel that should have outstanding quality, as well as a new and attractive look. In addition, its light weight and the resulting vehicle mass reduction ensure a very good ride quality. Then in 1970, cast aluminum wheels began to be used in mass production of cars, and a little later (1984) forged aluminum wheels as well. [16]

Steel Al alloy Mg alloy Ti alloy Composite

Figure 12. Car wheels made of different materials

The representation of aluminum wheels in 2000 was between 30 and 35% for European vehicles, and in the USA and Japan with more than 50%. Today, over 50% of worldwide vehicles use aluminum wheels, i.e. wheels represent almost 15% of the average aluminum content in passenger cars and pick-up trucks. Today, in North America, aluminum wheels are represented with approximately 70%, and in Japan with about 60%, while in Europe the representation is about 50% [16]. In recent years, the growth rate of the aluminum wheel market has slowed, but the market share is still growing. The development of new high-strength steels (HSS and AHSS) and sophisticated production methods have enabled a significant reduction in the weight of steel wheels.

Aluminum alloys must meet a number of conflicting requirements:

- to have good mold casting properties,
- to withstand the physical impact (deformation and impact strength),
- have corrosion resistance (normal and salty atmosphere) and
- have fatigue resistance.

These requirements have led to the use of subeutectic Al-Si alloys with 7 to 12% silicon content, different magnesium content (compromise between strength and elongation), low iron content and lower impurity concentration.

In the USA and Japan, only heat-treated alloy (T6) AlSi7Mg0.3 is used. In Europe, the share of heat-treated wheels is increasing, but it is still far from 100%; an AlSi7Mg0.3 alloy is also preferred. [16]

Non-heat-treated cast wheels are made either from AlSi7Mg0.3, mainly in France, or from AlSi11Mg, which contains less magnesium, mainly in Germany and Italy; this alloy is less favorable in terms of fatigue strength, but has a better casting ability and different shrinking characteristics. However, it is not suitable for heat-treated wheels. [16]

The experimental test results of Al-Si-Mg type alloys, with different Si and Mg contents, on static and dynamic loads showed that the heat-treated (T6) AlSi7Mg0.3 alloy offers the best compromise between fatigue strength and elongation. The same studies were conducted with different silicon contents. They have clearly shown that increasing the Si content also has a negative effect on ductility, especially at low degrees of hardening (thick hubs). However, alloys with 9-11% Si are still acceptable if better casting ability is required. Increasing the magnesium content does not clearly improve fatigue resistance, but significantly reduces ductility. [17]

Table 2 shows an overview of the most common alloys for the production of automobile wheels.

The wheels must provide critical safety functions and must meet high standards of design, engineering and construction. Almost all modern aluminum wheels are obtained by one or two processes: casting and forging. While the look of the wheels was the main motive for cast wheels, forged wheels are usually lighter and stronger, but also more expensive than cast wheels. However, with the right choice of materials and control of the casting process, cast aluminum wheels can have a high quality level and provide long-term reliable usage.

Today, cast aluminum wheels are most common with a market share of over 80% in North America, more than 90% in Europe and close to 100% in Japan. In North America, the share of forged wheels is about 15%, in Europe only 5% [17]. Increasing requirements for weight reduction represent a good opportunity for further growth of forged aluminum wheels, despite the higher price. Many studies are being conducted to further reduce the weight of the aluminum wheels without compromising the benefits of styling (e.g. aluminum foam wheel; Figure

Table 2. Basic alloys for the production of automobile wheels [16]

Percentage of the main alloying elements %		Commercial designation	Standards of appropriate or similar composition
Si Mg Mn	7 0,3 0,5	G-AlSi7MgMn	356.1 /USA/
Si Mn Mg	9 0,5 0,3	G-AlSi9MnMg	A 360.2 /USA/
Si	13	G-AlSi 13	A 413.2 /USA/ AlSi12 /Fe/ /JUS/
Mg Mn	3,5 0,3	P-AlMg3,5	5154 A.A /USA/ AlMg3.00 /JUS/
Si Mg	0,5 0,5	P-AlMgSi	6060 A.A /USA/ AlMgSi0,5.00 /JUS/
Mg Si Cu	1 0,6 0,25+Cr	AlMg1SiCu	6061 A.A /USA/ AlMgSiCu.00 /JUS/
Si Mg Mn	1 0,6 0,4+Cr	P-AlSi1MgMn	6080 A.A /USA/ AlSi1Mg.00 /JUS/

13) [18, 19]. Figure 14 shows wheels made by different technologies (casting and forging).

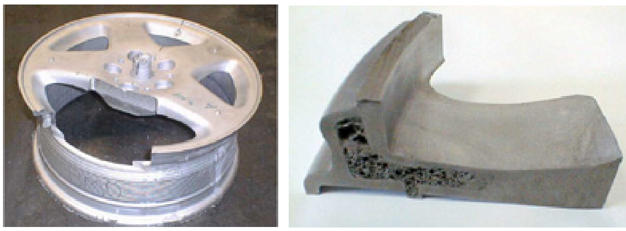


Figure 13. Aluminium foam wheel

a) b)

Figure 14. Wheels made by the process of a) casting and b) forging

Cast wheels provide high dimensional accuracy and corresponding static, dynamic and mechanical characteristics. An important reason for choosing cast aluminum wheels is their attractive visual appearance.

Different technologies are used for the production of cast wheels. The main casting processes used to produce aluminum wheels are:

- low pressure casting (mainly used),
- gravity casting in the mold (less used),
- extrusion process (used marginally).

Most cast aluminum wheels are manufactured under low pressure. During casting, a relatively low pressure (about 2 bars) is used to achieve a very fast filling of the mold and to obtain a uniform microstructure, which improves the mechanical properties compared to the gravity casting. [20]

Forged aluminum wheels are usually one-piece wheels formed from one block of metal by hot forging, followed by hot or cold spinning forming and other necessary processing operations (drilling, milling, scraping, polishing, etching, painting, etc.). The forging process allows flexibility in the design of the stylized disc, almost similar to a cast one. One-piece forging is considered superior to other forms of wheel production in providing ultimate strength while reducing weight compared to cast and multi-piece aluminum wheels (and of course steel wheels). Forged wheels are usually about 25% lighter than cast wheels (and potentially even more). Although casting can be a cheaper process, cast wheels show significantly lower mechanical properties than forged wheels. Forged wheels outperform cast aluminum wheels, especially in terms of impact and fatigue performance. The alloys most commonly used for forged aluminum wheels are: EN AV-AlSi1MgMn (6082) in Europe and AA-6061 (AlSiMgCu) in the USA. [17]

One-piece cast wheels are the most common type of aluminum wheels. In addition, there are multi-part wheels that consist of two or three components assembled together to produce a finished wheel. Multi-part wheels can use different production methods (e.g. a combination of casting and forging). Generally speaking, wheel parts offer the ability to customize wheels for special applications that would not otherwise be available. The parts are connected to each other with screws, and less often by welding and gluing. The multi-piece wheels were originally developed for racing in the early 1970s and have been used on cars ever since. There are many multi-part wheels options on the market now. The 2-piece wheel design does not offer as wide a range of applications as the 3-piece wheel; however, they are more common in the market, and their prices start well below the average 3-piece rims. Multi-piece wheels are produced in small quantities and due to high development and production costs they tend to be at the high end of the price scale. Figure 15 shows the appearance of a one-piece (monoblock), two-piece and three-piece car wheels.

a) b) c)

Figure 15. Aluminum wheels made as a) one-piece (monoblock), b) two-piece and c) three-piece

CONCLUSION

As the average weight of passenger cars has increased significantly since the 1970s, and as vehicle weight directly affects fuel consumption, less weight is now needed more than ever to reduce CO_2 emissions. Reducing the car's weight by 100 kg, lowers CO_2 from the exhaust by 8 grams per one km travelled.

Today, it is simply impossible to imagine the automotive industry without aluminum and its alloys. Aluminum is used to manufacture a number of car components, including the engine parts, bodywork and even interiors. Aluminum is an ideal lightweight material, as it allows weight savings of up to 50% compared to competing materials in most applications without compromising safety. Modern European cars contain an average of 180 kg of aluminum components with a trend of increasing to 200 kg by 2025. In the short term, it will be possible to realize many additional applications of aluminum without significant reengineering or a major impact on car price. This could easily reduce the average weight of cars produced in Europe by 40 kg. The industry is working to reduce the costs of other applications of aluminum, especially in the construction of bodywork, chassis and suspension parts, which are currently used in sports and luxury cars, so that they can find their place in smaller cheaper cars as well.

Nowadays, cast and forged one-piece and multi-piece aluminum wheels have reached a high level of technical development. However, there is still some potential for further improvement. This has been demonstrated, for example, by the recent introduction of aluminum foam wheels.

The problem with the use of aluminum is the price of this metal, since it is higher than the price of steel and plastic. By reducing the cost of aluminum, production and the use of modern processing technologies, it is certain that its application in the automotive industry will be more frequent.

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