ALUMINIUM AND Al-ALLOYS

Subject: Materials Science

MSc presentation
Széchenyi István University

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1. INTRODUCTION:

In the world of auto manufacturing, aluminium is kind of the new kid on the block. **It's being used increasingly in the car world for its lightweight but tough nature**. In **2009**, aluminium components made up about **9 percent of the weight** in most modern vehicles, compared with about **5 percent in 1990** and just **2 percent in 1970**.

Aluminium can be used in automotive manufacturing to create **body panels** for a lighter, more performance-oriented vehicle. Starting with the Acura NSX in the early 1990s, many supercars have been constructed out of aluminium, including the white-hot Audi R8. **Wheels** are also often made out of aluminium.

In addition, **more automakers are switching from traditional iron blocks for engines to aluminium construction.** It tends to be not quite as durable as iron, but **its lighter weight** means a big boost in performance.

(source: https://auto.howstuffworks.com).

2. PURE ALUMINIUM (ores and preparation):

The aluminium belongs to the group of the light metals. It is **the most important light metal** regarding the applications. It has great importance in the **Hungarian industry**, as **its ore, the bauxite** is the only metal ore which considerably has occurred in Hungary.

Aluminium is the **most abundant metal in the earth's crust** and is a constituent of many minerals.

Bauxite is the general name given to the hydrated oxides of aluminium. It contains varying amounts of combined **water and several impurities** of which ferric oxide and silica are usually predominant.

Extraction of the aluminium from the bauxite happens in **two steps**. In the first step **the alumina (Al_2O_3)** is extracted by **chemical purification**.

In the second step the **aluminium** (of 99…99.7% pure) is produced **by electrolysis**.

Bauxite

Al_2O_3

2. PURE ALUMINIUM (electric properties):

The **highest purity aluminium** used in the industry has **99.999%** of Al. This is extracted **by a repeated electrolysis** which needs a **double amount of energy**, therefore these are used in such cases, when the high purity is an important requirement.

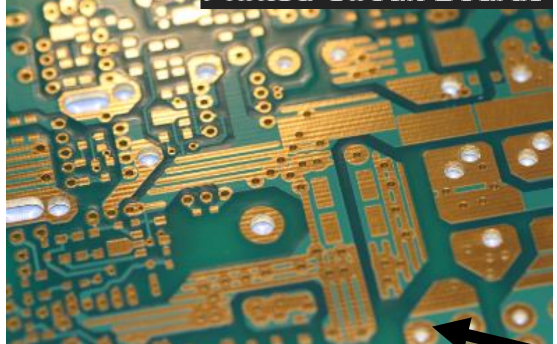
The high purity aluminium has the best **electric conductivity** after the gold, the silver and the copper, therefor it is used as the **material of electric cables** (lines).

The electric conductivity decreases with the alloying element concentration linearly or squarely and therefore the high purity aluminium is needed in the electricity.

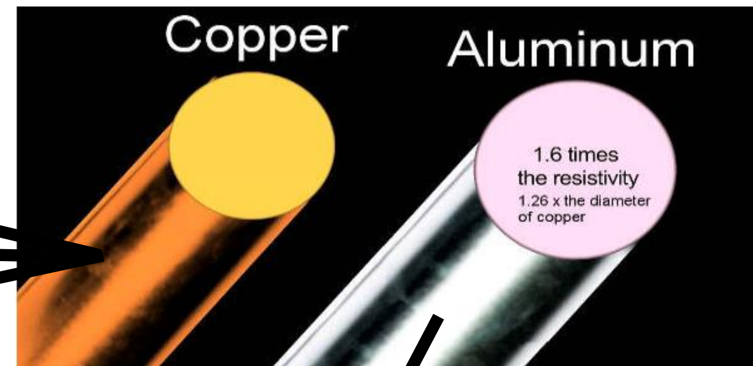
2. PURE ALUMINIUM (electric applications):

Electricity in long wires used in transmission behaves very differently than in **short wires** used in design of devices.

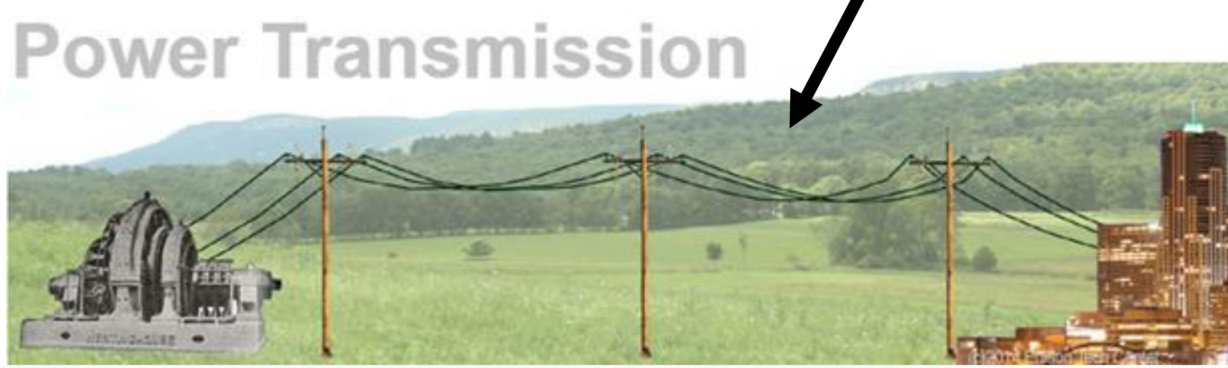

gold used in connectors for Motorola chips

Printed Circuit Boards



Transformers



All types of Electric Motors

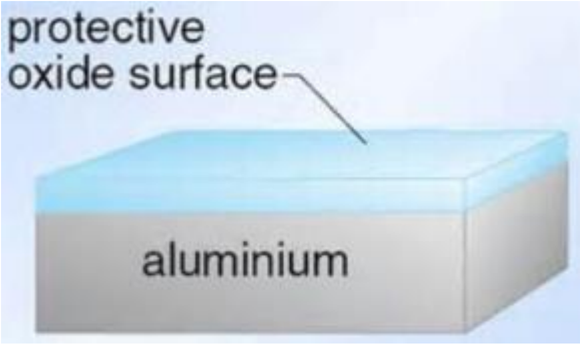


2. PURE ALUMINIUM (surface oxide layer):

Aluminium has a very **high affinity with oxygen**. (Only Beryllium has a higher affinity.) When a new aluminium **surface is exposed in the presence of air** (or an oxidising agent), it very **rapidly** acquires a thin**, compact, hard, tightly adhering, protective, self healing film of aluminium oxide** (about 0.5 µm in air). This film is relatively **inert chemically**.

It is on the inactivity of the surface film that the **good corrosion resistance** of aluminium depends. **When the surface film** dissolves, dissolution of the metal (corrosion) occurs; when the film suffers localised damage under conditions when self-healing cannot occur, localised corrosion follows.

The **corrosion resistance fails with several alloying elements** (e.g. Cu, Fe), because local galvanic cells evolve on the surface.



2. PURE ALUMINIUM (properties comparised to metals):

Some properties of commercially pure metals:

	Mg	Al	Ti	Fe
Density / $g\,cm^{-3}$	1.74	2.7	4.51	7.87
Modulus / GPa	45	70	120	210
Specific Modulus / $GPa\,cm^3\,g^{-1}$	25.9	26	26	27
Melting Temperature / °C	650	660	1670	1535
Crystal Structure (300 K)	h.c.p.	c.c.p.	c.p.h.	Cubic–I
Production per annum /tonnes	5×10^5	2×10^7	5×10^5	8×10^8
Energy Cost / $MW\,h\,tonne^{-1}$	??	70	130	15
Relative Cost	7.5	3.7	9	1.0

3. Al-ALLOYS (main alloying goals):

The alloying elements of the aluminium
– regarding their effect –
are rated in the following groups:

- For **increasing strength**: Cu, Mg, Si.
- For **improving the corrosion resistance**: Mn, Sb.
- For **grain refinement**: Ti, Cr.
- For **increasing the heat resistance**: Ni.
- For **improving the machinability**: Co, Fe, Bi.

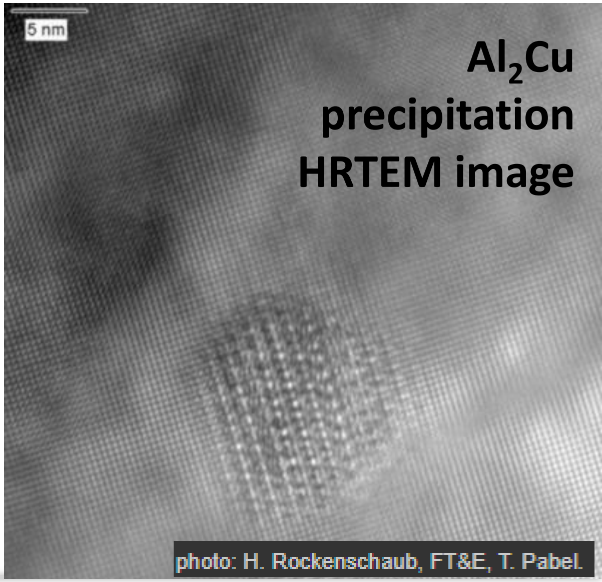
3. Al-ALLOYS (chemical compounds, contaminants):

The aluminium forms a hard and rigid **chemical compound** with most of its alloying elements, e.g. Al_2Cu, Al_3Mg_2, Al_3Fe,
the following elements are exceptions: Si, Bi, Cd, Zn.
The alloying elements can form **chemical compound with each-others**, as well.

Certain elements can be **contaminants** in given cases. The best example for that is the **Cu which can increase the strength the best**, however **it has to be avoided in the Al-alloys of corrosion resistance**.

As contaminant the role of the **iron** is important because it **decreases the corrosion resistance strongly**.

The **oxygen** (as the part of the Al-oxide) and the **hydrogen** (which is adsorbed during casting) always **are contaminants**.



3. Al-ALLOYS (solid solutions):

The aluminium forms a **solid solution with most of its alloying elements**, and the **solution always goes upto a limit**.

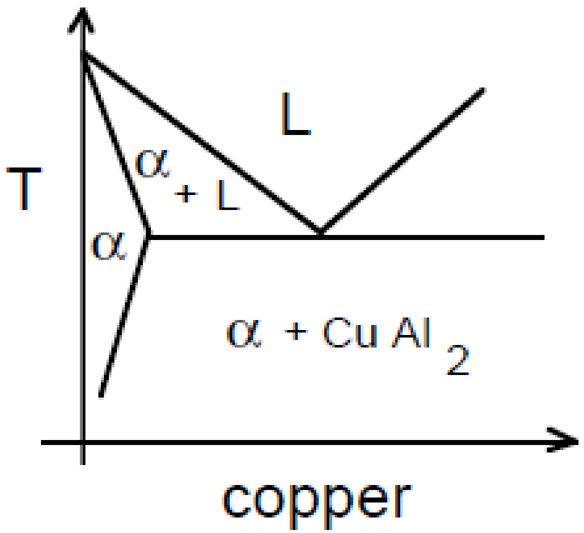
Up to 70 wt% of **zinc** can dissolve in aluminium
(at the melting point of the eutectic composition),

followed by **magnesium** (17.4 wt%),

copper (5.7 wt%) and

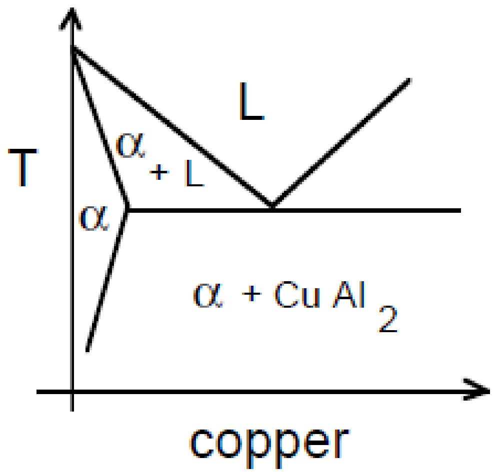
silicon (1.65 wt%).

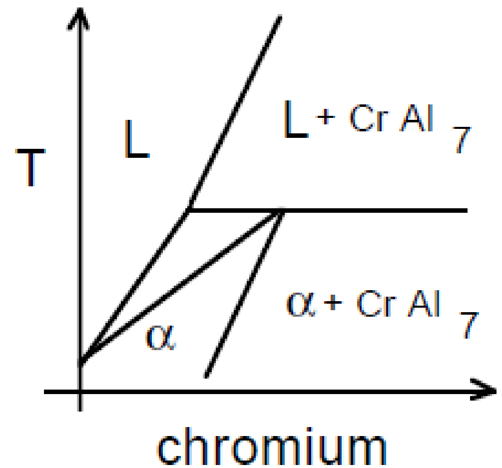
The solubility always decreases with the temperature.



3. Al-ALLOYS (characteristic types of phase diagrams):

Typical **eutectic** and **a peritectic phase diagrams** are illustrated in Fig. 1;
these two forms describe the vast majority of phase diagrams for aluminium alloys.
In most cases the eutecticum formation is characteristic
which can be seen in the left side (e.g. **Al-Cu, Al-Mg, Al-Si, Al-Zn**),
however **peritectic formation of chemical compounds**
shown in the right side sometimes can be characteristic, as well (e.g. **Al-Cr**).





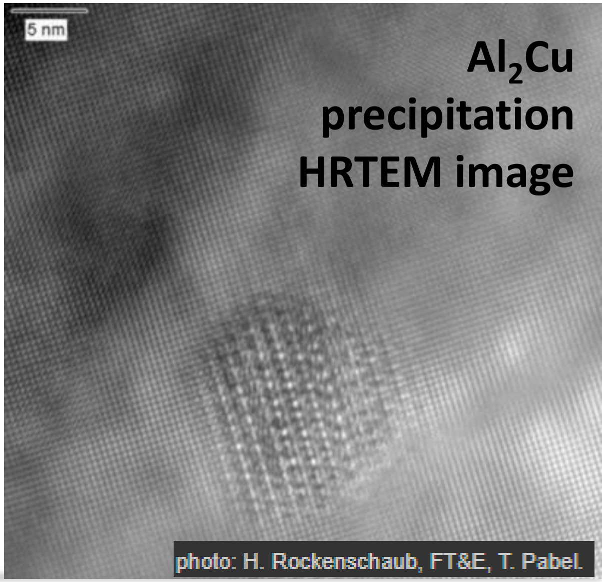
Since **there are no allotropic phase transformations** in aluminium, much of the control of microstructure and properties relies on **precipitation reactions**.
The solubility of solute in the matrix (α) is therefore **of importance**.

4. METALLURGICAL PRINCIPLES OF HEAT TREATMENT OF Al-ALLOYS

The **typical heat treatment** of the Al-alloys is **the age hardening** alias precipitation hardening, whose **goal is the increase of the strength** of the Al-alloy produced **by fine dispersed precipitations**.

This heat treatment is thus such a method, when **disperse precipitations arise in the ductile matrix of the α -solid solution**.

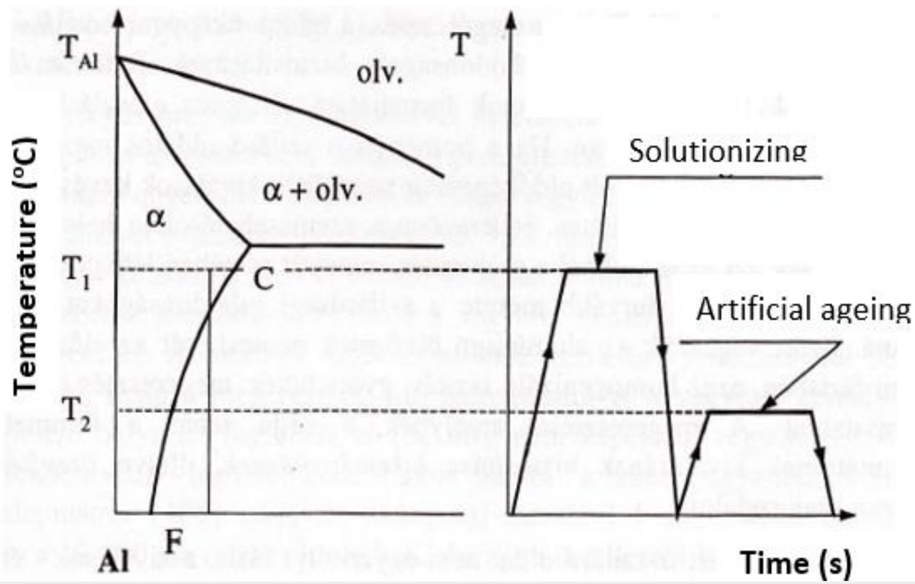
These precipitations – as it was shown similarly in the lesson of steels – increase the strength because they **are obstacles for the movement of the dislocations**, that is to say, they put up their effect by the dispersion strengthening mechanism.



4. METALLURGICAL PRINCIPLES OF HEAT TREATMENT OF Al-ALLOYS

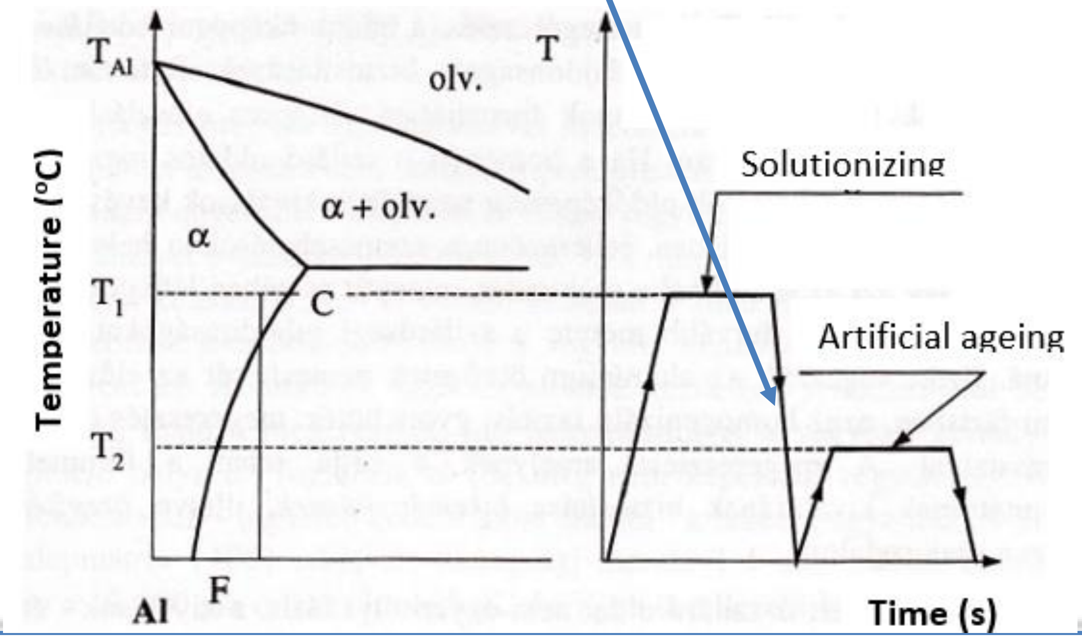
The first step of the precipitation hardening is the **solutionizing** which is carried out by **heating above the solvus temperature for a few hours**, and which results a **homogenous solid solution**. The goal of this solutionizing is the **full dissolution of the precipitations**, in order to insure the fine precipitations in the later phase of the heat treatment, which results the best favourable strength property. Therefore – in order to ensure the homogenous solid solution – the alloy has to be heated above the solvus line, the temperature of T_1 according to Figure 2, and it is kept on this temperature until the evolution of homogenous solid solution.

The **temperature of T_1 has to be chosen above the solvus line but below the eutectic temperature**.



4. METALLURGICAL PRINCIPLES OF HEAT TREATMENT OF Al-ALLOYS

After the solutionizing the alloy is cooled down (e.g. with water) to room-temperature, which is called **quenching**. The goal of the quenching is the **preventing of the formation of the precipitations in this step** of the heat treatment, that is, the goal is **creating a supersaturated α-solid solution**. This phenomenon is similar to the formation of the martesite (the supersaturated ferrite, the supersaturated α-solid solution) by the hardening heat treatment of the steel.



4. METALLURGICAL PRINCIPLES OF HEAT TREATMENT OF Al-ALLOYS

The formation of the supersaturated solid solution is **similar to the formation of the martesite** (the supersaturated ferrite, the supersaturated α-solid solution) by the hardening heat treatment of the steel.

The outcome is however fully other in case of the Al-alloys:

- **in case of the steels**, the **martensite is the hardest texture element**, it has the highest strength **because of the stressing effect of the carbon atoms trapped inside the α-solid solution**,

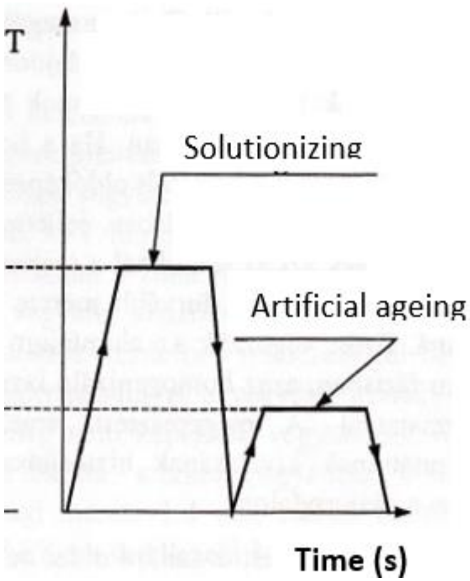
- **in case of the Al-alloys** however, the **strength increase** in the supersaturated α-solid solution **is small**, and **this alloy phase is not stable in the most cases**, *it has not got an own name as martensite in case of the steels*.

4. METALLURGICAL PRINCIPLES OF HEAT TREATMENT OF Al-ALLOYS

The second step of the precipitation hardening of the Al-alloys is the **artificial ageing,** which is **the true precipitation hardening.** The **temperature** of the artificial ageing **is about a quarter of the solutionizing temperature**. The criterion of the best strength properties is, that the **precipitations has to form in fine dispersed scattering in the matrix**.

In case of a **slow cooling**, the **precipitations could grow large** and they would be located at the grain boundaries, and these precipitations of larger measure would decrease the strength.

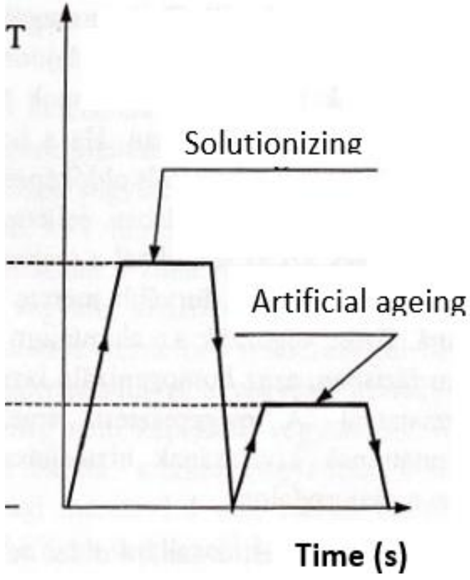
Therefor the **cooling after the artificial ageing has to be rapid**, as well.



4. METALLURGICAL PRINCIPLES OF HEAT TREATMENT OF Al-ALLOYS

As **the supersaturated α-solid solution is not an equilibrium phase (it is not stable)**, the formation of the **precipitations** (and the resulted strength increase) **can go off in given alloys without artificial ageing, over a long time period**, at room-temperature, this phenomenon is named by **natural ageing**.

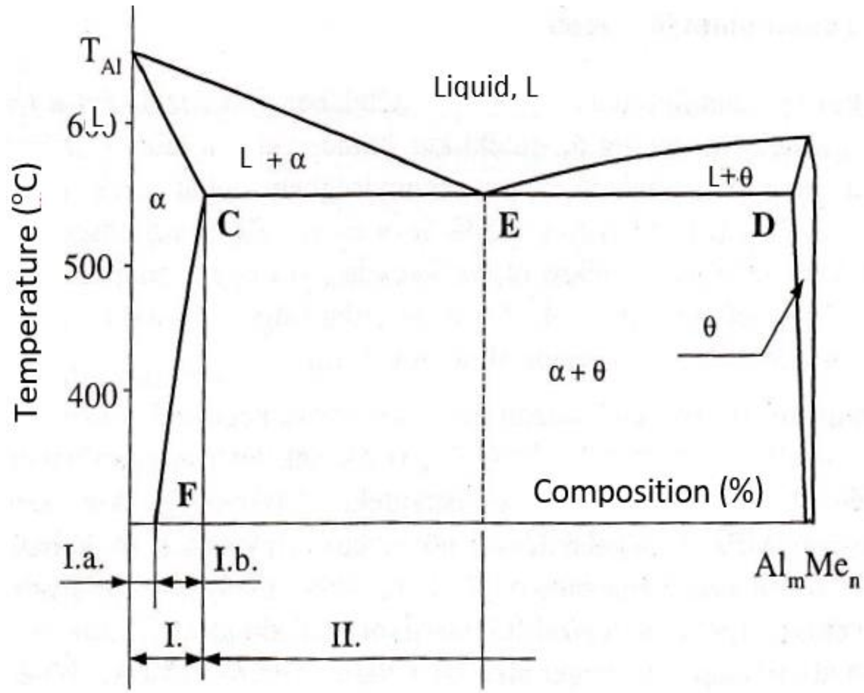
The **natural ageing** in Al-alloys is **very slow, it needs months, maybe years**, therefor, the **artificial ageing is a heat treatment of great importance**.



5. CLASSIFICATION OF INDUSTRIAL Al-ALLOYS

A classification of the industrial Al-alloys can be made according to the phase diagram characterizing the Al-alloys.

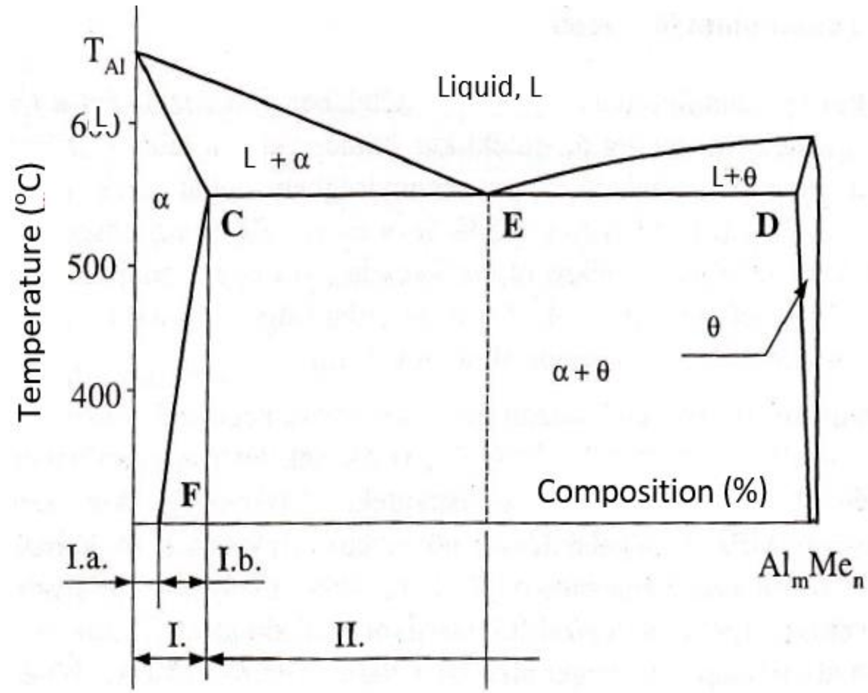
- The alloys which contain **smaller amount of alloying element than the saturated α-solid solution** (alloys which have α-solid solution predominantly) are the so called **wrought Al-alloys** (interval signed by I. in Figure 3).
- The alloys which have more amount of alloying element are the so called **casting Al-alloys** (interval signed by II. in Figure 3).



5. CLASSIFICATION OF INDUSTRIAL Al-ALLOYS

The wrought Al-alloys are divided for two different groups:

- the **non-heat treatable** Al-alloys contain 100% α-solid solution at room temperature (interval signed by I.a. in Figure 3),
- the **heat treatable** Al-alloys are the alloys being at the right side of the solvus, that is, where the vertical line signing a given composition crosses the solvus (interval signed by I.b. in Figure 3).



5. CLASSIFICATION OF INDUSTRIAL Al-ALLOYS

In the above part of this lesson we could see that the strength of the Al-alloys can be improved by alloying (Cu, Mg, Si) and heat treatment. In case of the wrought Al-alloys the strength can be improved by plastic forming, as well. In order to see the effectiveness of the different strengthening methods, **let us see the following example**:

- the tensile strength of the **primary aluminium** (Al 99,5) is about R_m=100Mpa,
- **alloying** of about 4% Cu, 2% Ni and 1.5% Mg increases the strength to the double value,
- after a **heat treatment** the strength increases to triple,
- if the alloy was **hot forged** before the heat treatment, the strength can reach to fourfold, to about R_m=400Mpa.

If all the three strengthening method are applied, a **fourfold strength increase can be reached**.

5. CLASSIFICATION OF INDUSTRIAL Al-ALLOYS

Regarding the above strengthening possibilities, the wrought and the casting Al-alloys are divided to separated groups.

The structure, the properties, the strengthening possibilities, the technologies and the applications are different in case of the two groups:

- The **wrought Al-alloys** generally are **sheet metals** and they are applied in **car body elements**.
- The **casting Al-alloys** – as their name indicates – generally are casts (ingots) and they are applied in materials of the **internal combustion engines** (cylinder blocks).

These two groups will be detailed in the following chapters.

6. WROUGHT Al-ALLOYS

The **main alloying elements** of the wrought Al-alloys are:

- copper (Cu),
- magnesium (Mg),
- silicon (Si) and
- zinc (Zn).

Their **amount is less than the composition of the saturated solid solution** at the temperature of the eutecticum, that is, the wrought Al-alloys can contain maximum:

- Cu of 5%,
- Mg of 10%,
- Si 1,5% and
- Zn of 4%.

6. WROUGHT Al-ALLOYS (NON HEAT TREATABLE)

From the group of the **non heat treatable wrought Al-alloys**:

- The **Al-Mg alloys** of two components, the so called **hydronalium**s are known about their **sea-water resistance**. Their relatively small strength can be increased by cold forming (R_m=200-300MPa).

- The **Al-Mn alloys** can be characterized by **excellent corrosion resistance**. They are applied in the food industry (e.g. milk transporter containers). They are alloys of small strength: their tensile strength is smaller than 150Mpa without forming.

6. WROUGHT Al-ALLOYS (HEAT TREATABLE)

The **heat treatable wrought Al-alloys** generally have **three or more components**:

- One of their different types is the so called **duraluminium** which contain components of **Al, Cu and Mg**. The tensile strength of these alloys (having about 4% Cu and 2% Mg) can be increased up to **500MPa by precipitation hardening**.

- The **Al-Cu-Ni alloys** can be heat treated to **large strength**, as well (R_m=400MPa). As they contain Ni, their **heat resistance** is better than for other Al-alloy groups.

Both of Al-Cu-Mg and Al-Cu-Ni alloys are of **high strength**, however their fault is, that the alloying element of Cu - applied to improve the strength – makes them **sensitive against the corrosion**.

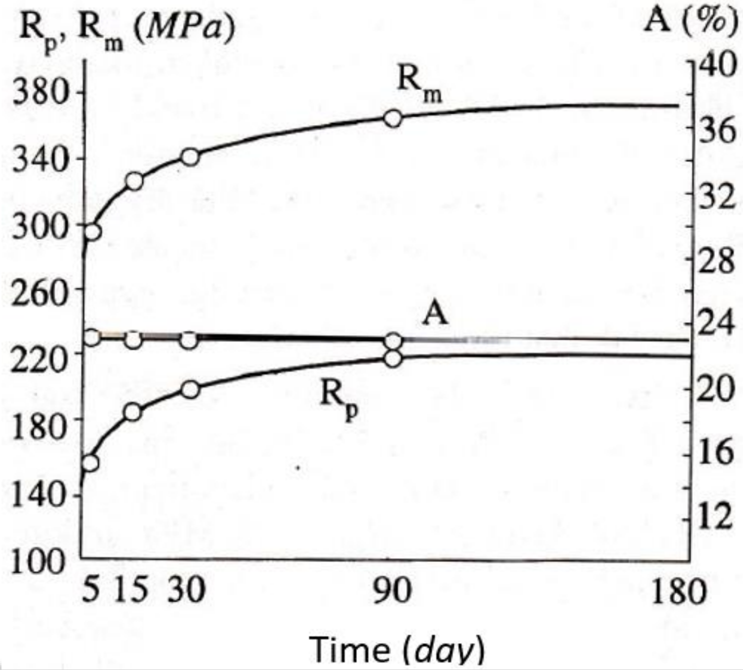
6. WROUGHT Al-ALLOYS (HEAT TREATABLE)

- The **Al-Zn-Mg-Ti weldable alloys** are the characteristic examples of the **naturally ageable Al-alloys**. Figure 4 shows the hardening process after a rapid cooling from 400 ^{o}C.

  The alloy is **soft and well formable in the first one-two days** after the heating and rapid cooling. It reaches the **final strength after 90-180 days**.

  The tensile strength is approximately 400MPa, the yield strength is approximately 200MPa, however its elongation is significant after at the end of the process, it is about 20-22%.

  A **disadvantage** is that the alloy **tends to corrosion because of the component of Zn**.



6. WROUGHT Al-ALLOYS (HEAT TREATABLE)

- The **Al-Si-Mg alloys** contain about 1,5% Si and 1,5% Mg. The strength is moderately high (R_m=400MPa), because they do not contain Cu, at the same time: the corrosion resistance is excellent because of the absence of the Cu.

Applying further **additional alloying elements**, some properties can be improved further, e.g.:

- an amount of 2% **nickel (Ni)** raises the **heat resistance**,
- an amount of 1-2% **manganese (Mn) improves the corrosion resistance**, mainly the sea-water resistance.

6. WROUGHT Al-ALLOYS (HEAT TREATABLE)

The chemical composition of the wrought Al-alloys is controlled by **the standard of EN 573-3:1995**.

The **international standard terminology** used in the aluminium industry is given in the Table.

Alloy Designation	Detail
1XXX	99% pure aluminium
2XXX	Cu containing alloy*
3XXX	Mn containing alloy
4XXX	Si containing alloy**
5XXX	Mg containing alloy
6XXX	Mg and Si containing alloy*
7XXX	Zn containing alloy*
8XXX	Other alloys
Heat Treatment Designation	**Detail**
F	As–fabricated
O	Annealed
H	Strain hardened
T	Heat treated
T4	Solution treated
T6	Solution treated and aged

6. WROUGHT Al-ALLOYS (HEAT TREATABLE)

Standard terminology:

*indicates precipitation hardened alloys with strength up to 600 MPa.
** indicates casting alloys.

The silicon–rich casting alloys are often sodium–modified.

Condition T4 includes ageing at ambient temperature.

Alloy Designation	Detail
1XXX	99% pure aluminium
2XXX	Cu containing alloy*
3XXX	Mn containing alloy
4XXX	Si containing alloy**
5XXX	Mg containing alloy
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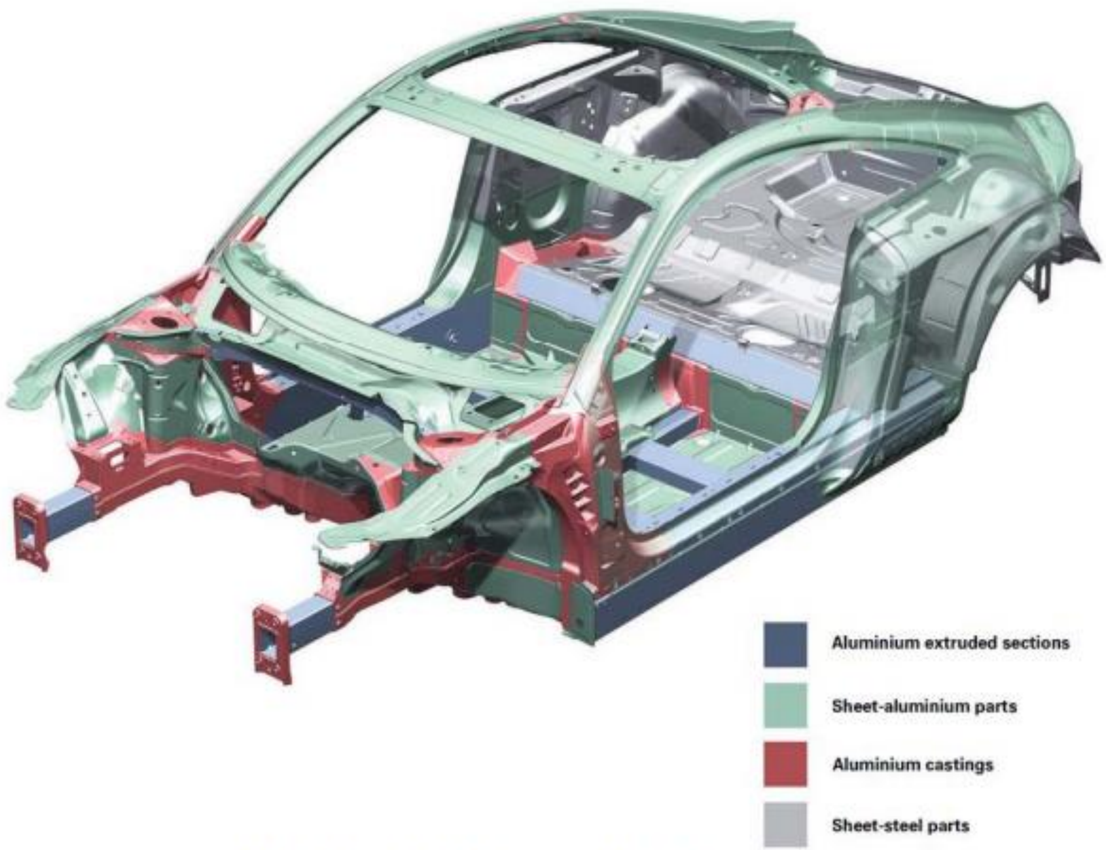
8XXX	Other alloys
Heat Treatment Designation	**Detail**
F	As–fabricated
O	Annealed
H	Strain hardened
T	Heat treated
T4	Solution treated
T6	Solution treated and aged

6. WROUGHT Al-ALLOYS (Application of wrought Al-alloys in car bodies)

Different **car body elements of the light cars are prepared by wrought Al-alloys**, which significantly contributes to the **mass reduction** of the cars (compared to the steel car bodies).

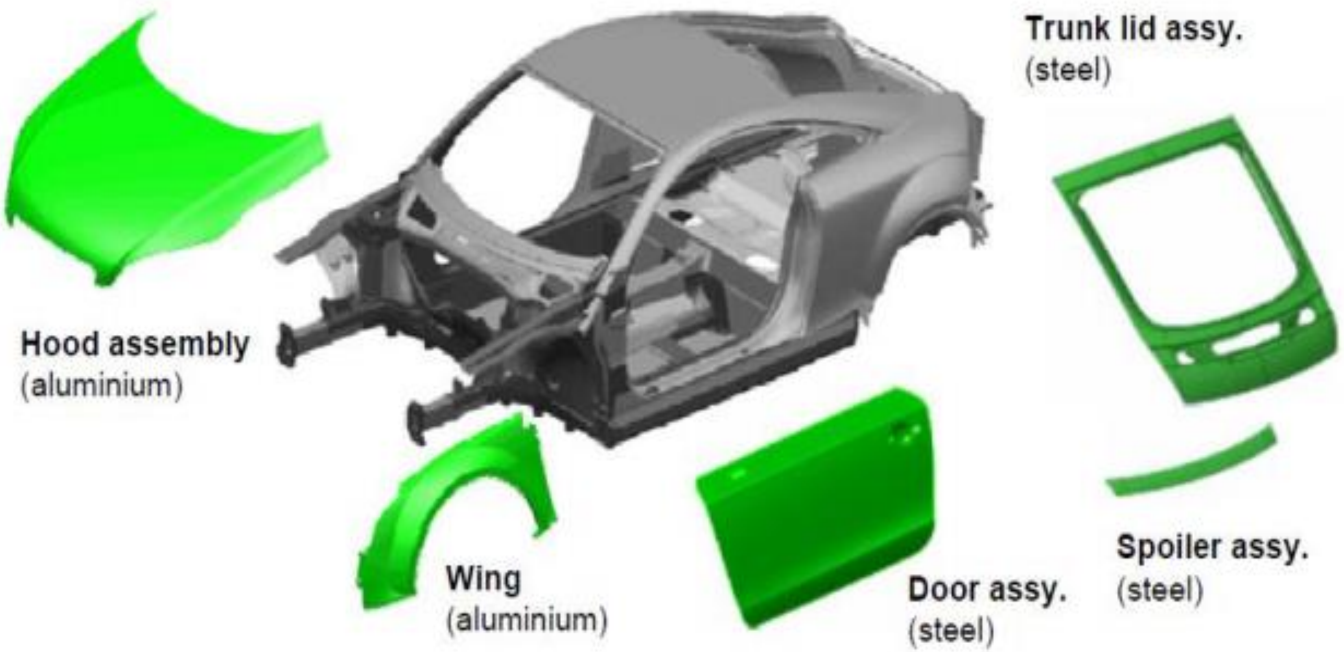
In the figure the car body of **Audi TT coupe** is shown. The materials are: sheet, extruded and casting Al-alloys, furthermore sheet steels.



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

Source: The Aluminium Automotive Manual, 2013: https://www.european-aluminium.eu/media/1543/1_aam_body-structures.pdf

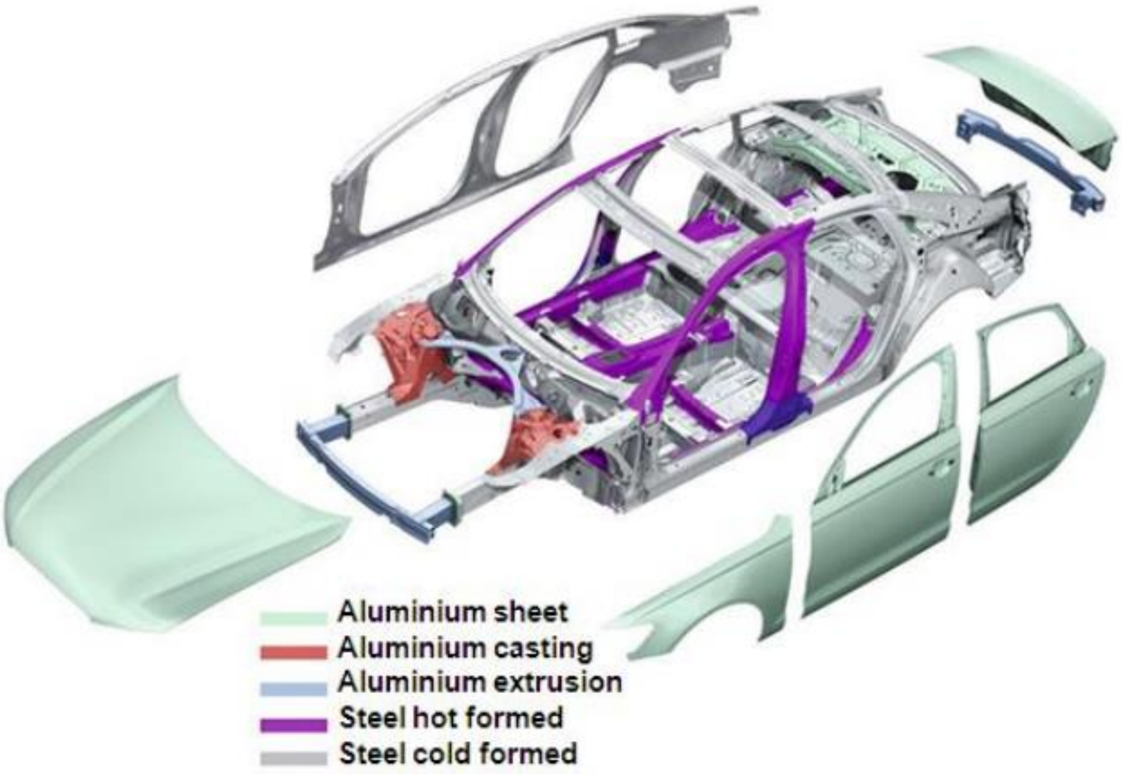
6. WROUGHT Al-ALLOYS (Application of wrought Al-alloys in car bodies)



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

Source: The Aluminium Automotive Manual, 2013: https://www.european-aluminium.eu/media/1543/1_aam_body-structures.pdf

6. WROUGHT Al-ALLOYS (Application of wrought Al-alloys in car bodies)



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

Source: The Aluminium Automotive Manual, 2013: https://www.european-aluminium.eu/media/1543/1_aam_body-structures.pdf

7. CASTING ALUMINIUM ALLOYS

The **strength properties** of the cast Al-alloys generally are **weaker than for wrought Al-alloys**. The tensile strength is **influenced by the cast technology**, as well. It is **smaller in case of sand casting**, and it is **larger in case of casting mould**. The Al-Cu-Ni and the Al-Mg-Si alloys are **heat treatable alloys**. Their tensile strength can be increased up 300 MPa by age hardening.

The casting Al-alloys can be categorized into **three groups according to the main alloying element**:

- the **silicon group** (Al-Si alloys),
- the **magnesium group** (Al-Mg alloys) and
- the **copper group** (Al-Cu alloys).

7. CASTING ALUMINIUM ALLOYS (Al-Si GROUP)

The **most outstanding casting alloys** belong to the **silicon group**. The characteristic types are the Al-Si and the Al-Si-Mg alloys. The amount of the silicon correspond to the **Al-Si eutectic composition** (Si=12%) which has a determined **melting temperature: T_m=578 °C**.

The **shrinkage of the eutectic composition** (1-1,15%) **is smaller** than for other Al-alloys (1,25-1,5%), moreover, it is **smaller in case of casting mould** (chill-mould) (0,5-0,8%), and therefor they are cut out for casting mould. The **strength is better than for the other groups**.

Al-Si alloys – where the **chemical composition deviates from the eutectic composition** – are used in different applications, as well, e.g.

- AlSi7Mg alloys are used **for additive manufacturing** (for laser melting),
- the so called **hypereutectic Al-Si alloys** (c>12%) often are used as material of the **cylinder block** in internal combustion engines.

7. CASTING ALUMINIUM ALLOYS (Al-Mg GROUP)

The second cast Al-alloy group, the group of the **Al-Mg cast alloys** is known as hydronalium, however hydronalium is the common name of the Al-Mg sheet form alloys (wrought Al-Mg alloys) and cast alloys.

These are alloys predominantly of aluminium, with between **10%-12% of magnesium as the primary alloying ingredient**. They also include a secondary addition of manganese, usually between 0.4%-1%. This alloy family is noted for its **resistance to seawater corrosion**. As such it is used in sheet form for **boatbuilding and light shipbuilding**. As castings it is used for **marine fittings**.

The reliable strength of some grades is sufficient **for aerospace use** and so they are used **for wetted components of seaplane aircraft**, such as floats and propellers, where marine corrosion resistance is also needed. Some variants of the alloy are ductile enough to be drawn into wire. This, combined with their resistance to corrosion by salty sweat, has led to an application **for violin strings** as an alternative to silver.

7. CASTING ALUMINIUM ALLOYS (Al-Cu GROUP)

The third cast Al-alloy group has the main types of **Al-Cu and Al-Cu-Ni cast alloys**.

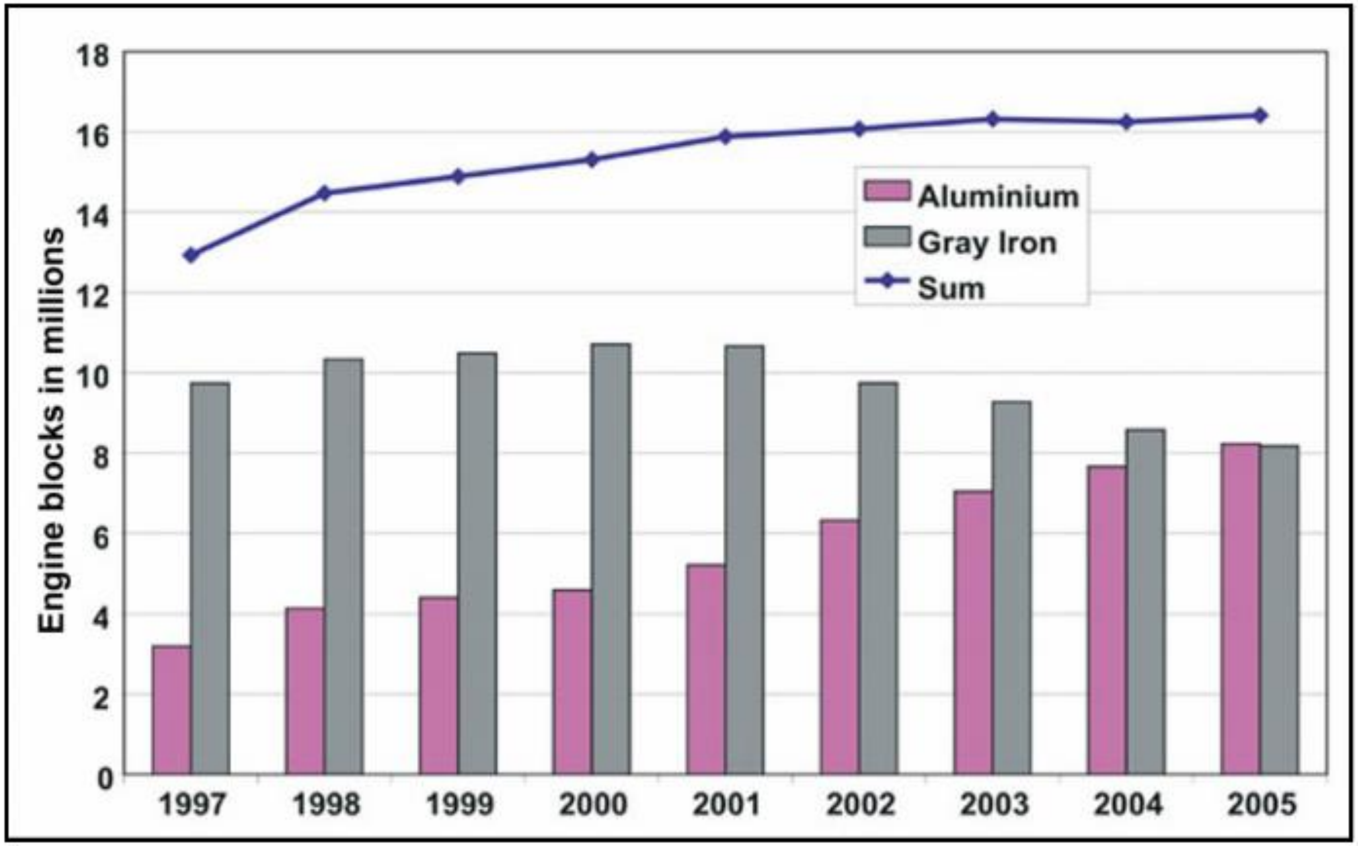
These are the **least disposed to the formation of the shrinkage cavities in case of casting** technologies.

Good thermal conductivity and certain degree of heat resistance are characteristic for this group. In case of additional alloying ingredients (0.2% Si and 0.3% Mg) they can be cut very good.

The **Ni ingredient improves the heat resistance**.

The Al-Cu-Ni cast alloys are used as materials of the **cylinder heads and the pistons**.

7. CASTING ALUMINIUM ALLOYS (Applications in car engines)



Production numbers of engine blocks in Western Europe (grey iron and aluminium cast alloys) (Source: https://www.european-aluminium.eu/media/1573/aam-applications-power-train-2-engine-blocks.pdf)

7. CASTING ALUMINIUM ALLOYS (Applications in car engines)

Grey cast iron and aluminium HPDC engine blocks

(Source: https://www.european-aluminium.eu/media/1573/aam-applications-power-train-2-engine-blocks.pdf)

7. CASTING ALUMINIUM ALLOYS (Applications in car engines)

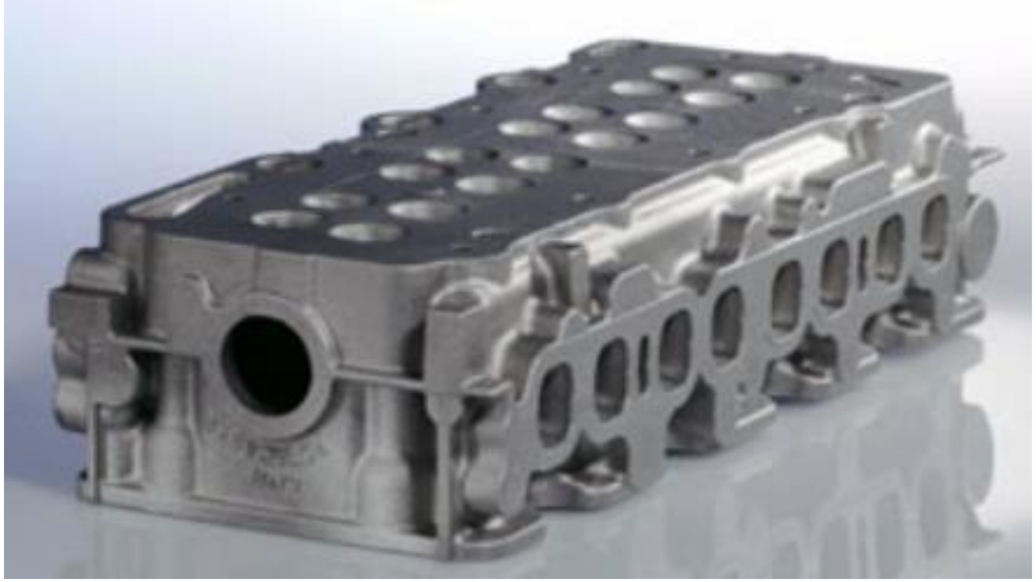
Commonly and occasionally used alloys and heat treatments for cylinder heads
(composition of the casting according to EN 1706)

Alloy	Si	Fe	Cu	Mn	Mg	Ni	Zn	Ti	Used Tempers
EN-AC-AlSi8Cu3 1)	7.5-9.5	0.8	2.0-3.5	0.15-0.65	0.05-0.55	0.35	1.2	0.25	F, T4, T5
EN-AC-AlSi6Cu4 2)	5.0-7.0	1.0	3.0-5.0	0.2-0.65	0.55	0.45	2.0	0.25	F, T4, T5
EN-AC-AlSi7Mg0.3	6.5-7.5	0.19	0.05	0.10	0.25-0.45	0.03	0.07	0.08-0.25	T6
EN-AC-AlSi7Mg 3)	6.8-7.2	0.45	0.15	0.35	0.25-0.65	0.15	0.15	0.05-0.20	T6
AlSi7MgCu0.5 4)	6.5-7.5	0.19	0.4-0.6	0.10	0.25-0.45	0.03	0.07	0.08-0.25	T6
EN-AC-AlSi9Mg	9.0-10.0	0.19	0.05	0.10	0.25-0.45	0.03	0.07	0.15	T6
EN-AC-AlSi10Mg(Cu)	9.0-11.0	0.65	0.35	0.55	0.20-0.45	0.15	0.35	0.15	T6

1) A380.2, VDS 226 3) LM25 2) A319, VDS 225 4) not standardized

(Source: The Aluminium Automotive Manual, 2013: https://www.european-aluminium.eu/media/ media/1580/aam-applications-power-train-4-cylinder-head.pdf)

7. CASTING ALUMINIUM ALLOYS (Applications in car engines)



Isuzu diesel 4-cylinder head, alloy EN-AC-AlSi7Mg / T6 temper
(Source: The Aluminium Automotive Manual, 2013: https://www.european-aluminium.eu/media/ media/1580/aam-applications-power-train-4-cylinder-head.pdf)