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VŠB - Technical University of Ostrava
Faculty of Metallurgy and Materials Engineering

Casting of non-ferrous metal alloys

(study support)

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STUDY REGULATIONS

Foundry of non-ferrous metal alloys

For the subject "Foundry of non-ferrous metal alloys" in the 1st semester of the follow-up Master studies you have obtained an educational packet including integrated lecture notes for the combined study comprising also study regulations.

Prerequisites

Knowledge of fundamentals of foundry.

The objectives of the subject and outputs from the education

The subject is aimed at theoretical and practical aspects of manufacture of castings from non-ferrous metals and alloys. The attention is particularly paid to the most frequently used materials based on aluminium, copper, and magnesium, partly also to alloys of titanium, zinc, lead, tin, etc. The subject deals with problems of melting, casting, and thermal treatment of these materials. Specific defects of casting from these alloys including their identification and prediction are here presented too.

Acquired knowledge:

- *the student will be able to characterize the basic terms from the area of Foundry technology of non-ferrous metals and alloys*
- *the student will be able to formulate and describe the basic characteristics of each of the non-ferrous metals and alloys*

Acquired skills:

- *the students will be able to use their knowledge to the decision about the suitability of the application of the materials for the castings production,*
- *the students will be able to apply their theoretical knowledge to suggest and adjust the technology and metallurgy of castings production*

Recommended procedure for studying each chapter:

Each chapter needs to be comprehended thoroughly, including figures and equations. Behind each chapter, there is a summary and questions relevant to the respective text. The time required for the study is suggested, but this is for information only and depends on an individual approach of a particular student.

A way to communicate with lecturers:

For the students of the combined form of study, possibilities to communicate with a lecturer are above all in agreed individual consultancies on the given topic. More detailed instructions will be discussed with students at the beginning of the course in which students will be present.

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1. Division of non-ferrous metal alloys

Time to study: 3 hours

Aim: After study of this chapter you will know

- Basic division of non-ferrous metal alloys
- Properties and utilization of basic non-ferrous metal alloys
- A comparison of metal consumption

Lecture

Division of non-ferrous metal alloys:

- according to the basic element – usually more than 50 %
- according to the processing method – according to the technology (foundry and forming)
- according to the density
  - light (Al, Mg, Ti)
  - heavy (Cu, Zn, Ni, Pb, Sn) – 4500 kg.m^{-3}
- according to the melting temperature
  - up to 600°C – with low melting temperature (Sn, Pb, Zn)
  - up to 1500°C – with medium melting temperature (Mg, Al, Cu)
  - with high melting temperature (Ti, Cr, V, Mo, Nb)
- according to the chemical reactivity
- or according to other criteria

Division of non-ferrous metals

Pure metals are basically represented by individual elements that is why the periodic table of elements can be used to divide the metals.

From the technical point of view, the most common usual division of metals is the following:

1. Metals with low melting temperature: Zn, Cd, Hg, Sn, Pb, Bi
2. Light metals: Al, Mg, Be, Ti
3. Metals with medium melting temperature: Cu, Ni, Mn, Co
4. Precious metals: Au, Ag, Pt, Rh, Pd, Ir, Os
5. Metals with high melting temperature: Cr, W, V, Mo, Ta, Nb

The labeling methods of non-ferrous metals

Numerical labeling

- corresponding European, national, company or other norms
- usually the chemical composition of the alloy is not clear from this labeling

Labeling by chemical labels

- states the mean percentage content of the main elements
- the symbol of the main element is on the first place
- the symbols of other elements are on the next places in order of their content in the alloy
- the amount of the element with less than 1 % of the content is usually not state
- e.g. AlSi10Mg (silumin with 10% silicon and less than 1% magnesium)

Metals with low melting temperature

The most important from the technical point of view:

Lead,
Tin,
Zinc.

Lead – Pb

Pb is a metal of grey color, very soft and well formable. It resists very well to strong inorganic acid

- it is a poor conductor of heat and electricity,
- Pb is toxic, therefore it cannot be used in food-processing industry.

Main applications of Pb

- protection of containers and pipelines during the production of H_2SO_4,
- protection of electrodes in car batteries,
- protection against radiation (X-rays, radioisotopes),
- Pb alloys – soft brazing solders.

Tin – Sn

Sn is a silver-white metal, well formable, a little bit harder than lead but still very soft.
Sn resists the corrosion well, it is stable in air and in water.

Main applications of Sn

Approximately half of the produced Sn is consumed for the surface protection of objects, especially for food-processing purposes, the other half of produced Sn is consumed in alloys with low melting temperature (soft brazing solders, tin compositions) and together with Cu it is used to produce bronze.

Zinc – Zn

Zn is a white metal with blue-grey hue, medium hard and brittle at normal temperatures. It resists well to atmospheric influences, seawater and organic substances.

Main application of Zn

- Surface protection, especially of steels,
- the alloys of Zn are very important, such as zinc oxide ZnO (white color in paintings) or so-called white vitriol (used in medicine for galvanization).

Light metals

The most important from the technical point of view:

Aluminum,
Magnesium,
Titanium.

Aluminum – Al

Al is the most abundant metal in earth´s crust and the second most consumed after Fe.

At normal conditions, Al is very stable, after heating it becomes very reactive and creates mainly oxides.

Bauxite ore is the most important for the production of Al. It is basically Al_2O_3 with and undefined content of bound water.

Main applications of Al

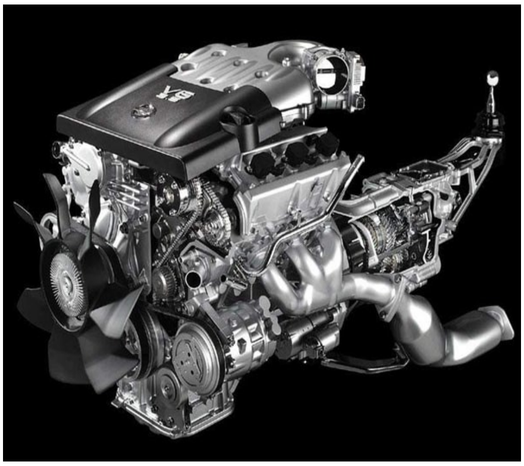
- electrotechnical industry (electric conductive material, condensers),
- chemical and food-processing industry (good thermal conductivity and corrosion resistance in acidic environment),
- cases and protective coatings,
- a large part of Al is consumed in the production of Al alloys (alloys for forming, casting alloys with a wide range of applications especially in the automotive and aviation industries).

Applications of aluminum and its alloys:

- engineering (castings, construction parts, various profiles, etc.)

- building industry (façade profiles, profiles for doors and windows, etc.)

- food-processing industry (packaging – aluminum foil),
- eletrotechnics (cables, wires),
- aviation industry (alloys based on Al-Li are used),
- automotive industry (parts of engines, profiles for engine parts, profiles for doors filling, cases of dampers, etc.)



Titanium – Ti

Ti is a non-magnetic polymorphic metal, the importance of which increased considerably after the World War II.

The main advantage of Ti are the low specific weight and at the same time high strength (tenacity equal or even harder than steels), good notch toughness even at low temperatures and good corrosion resistance.

The main disadvantage of Ti is the difficult processing, due to the high reactivity of Ti at temperatures higher than 700°C.Ti also has worse machinability, castability and weldability.

Main applications of Ti:

- chemical, paper and textile industries (especially used for its resistance to Cl and its compounds),
- ship parts (used for its excellent resistance to sea water),
- aviation and automotive industries,

- medical intoxicity of Ti enables the usage in food processing and pharmaceutical industries,
- surgery (tools, screws, implants),
- Ti alloys (used especially when Al alloys are not suitable).

Metals with medium melting temperature

The most important from the technical point of view:
- copper,
- nickel,
- manganese.

Copper – Cu

Cu is a reddish metal with excellent thermal and electrical conductivity, very good formability at high and low temperatures – it keeps its formability even at negative temperatures.
It has very good corrosion resistance against atmospheric conditions as well as against a number of chemicals.
Cu is the third most used metal after Fe and Al. Among its advantages, there are good machinability, and weldability, on the other hands, it has poor castability.

Main applications of Cu:

- in electrotechnic industry as the electricity conducting material,
- equipment exposed to low temperatures,
- roofing, gutters and downspouts,
- containers in food processing industry,
- steel sheets cladding,
- approximately a half of produced Cu is used to produce alloys, namely brass or bronze.

Nickel - Ni

Ni is an expensive ferromagnetic metal with a very good corrosion resistance and good mechanical properties.
High notch toughness is an important feature of Ni even at low temperatures.

Main applications of Ni:
- approximately 60 % of Ni is consumed as an ingredient in alloyed steels, where it increases the notch toughness at low temperatures,
- in electrotechnical industry, the Ni is used for regulatory resistance or resistance thermometers,
- as a construction material it is used for valve seats or as a part of steam valves,

- approximately 25% of Ni is consumed in Ni alloys (alloys with special physical properties and alloys that are temperature-resistant.

Manganese - Mn

Mn is a gray metal, hard and brittle.
It oxides relatively quickly on air, it dissolves in acids and decomposes water.

Main applications of Mn:

- the most of Mn is consumed as an ingredient of steels – it is one of the most commonly used ingredient in cheap alloyed steels, where it acts most to increase toughness.
- Mn is often a part of iron ore that is why it becomes a part of steel even as a natural ingredient, similar to Si, P or S.

Precious metals

The most important from the technical point of view:

- Gold,
- Silver,
- Platinum.

Gold - Au

Au is a yellow metal – it is the best known one from the previous metals, especially because it was used also as a currency and is considered to be the most precious metal in jewelry.
It is an excellent conductor of electric current and heat, it is not exceptionally tough and it is very formable (at low temperatures it is possible to create a thin film only 0.0001 mm thick).
It has an excellent corrosion resistance, it is the second most chemically resistant metal after Pt.

Main applications of Au:

- Electrotechnical industry (conductors, gold plated contacts),
- jewelry
- Au alloys

Silver - Ag

Ag is a white metal with very good corrosion resistance.
It has the best thermal and electrical conductivity of all metals.
Silver nitrate AgNO3 is a very well-known compound. It is used in medicine and especially in photography (photosensitive layer).

Main applications of Ag:

- Electrotechnical industry (wires, fuses, contacts),
- jewelry,
- protective layers on parts for chemical industry,
- Ag alloys (used in electrotechnical industry as hard solders).

Platinum - Pt

Is the main representative of the group of so-called platinum metals (Pt, Pd, Rh, Ir, Os).
Pt is characterized mostly by its high chemical stability and resistance against oxidation at high temperatures – it the most resistant metals of all.
Like all precious metals, it also belongs to the most expensive metallic materials.

Main applications of Pt:
- Electrotechnical industry (special tubes, switches, potentiometers, spark plug electrodes),
- Laboratory cups and bowls,
- Nozzles for the production of glass and synthetic fibers,
- Catalyst in chemical and pharmaceutical industry,
- Pt alloys (heating elements, thermocouples).

Metals with high melting temperature

The most important from the technical point of view:
- chromium,
- molybdenum,
- tungsten.

Chromium - Cr

Cr is a white metal with a blue hue, shiny and hard, very stable on air.
The Cr compounds are toxic and usually markedly colored. That is why they are used as dye.

Main applications of Cr:
- it is used as an ingredient in so-called corrosion-resistant steels (steels used in chemically aggressive environment) – corrosion-resistant steels have to theoretically contain more than 11.5% Cr (practically more than 14% Cr). In smaller quantities, Cr increases the hardenability of steels.
- Another important are of Cr use is the galvanic electroplating of various parts and objects, which are this way protected against oxidation and have a shiny and smooth surface.

Molybdenum - Mo

Mo is a hard, brittle metal, chemically stable with high melting temperature.

Main applications of Mo:
- The most of Mo is consumed in the production of steels, where it acts to increase hardenability, corrosion resistance etc.

- Mo is also used to produce cemented carbides for cutting tools,
- In the electrotechnical industry for contacts,
- Magnetically soft alloys,
- tubes,
- X-ray tubes,
- Resistive materials in vacuum at temperatures of 1600 to 2000°C,
- Its good corrosion resistance is used in the manufacturing of valves, mixers and tanks in chemical industry.

Tungsten - W

It has properties similar to Mo, its melting temperature is the highest among metals.
It forms hard and stable carbides.

Main applications of W:

- It is the typical additive metal in tool steels, especially in so-called high-speed steels (it increases the resistance against abrasion and corrosion of the tools),
- Furthermore it is used in steels that work at higher temperatures and in steels with high hardness,
- W is also used for contacts with good wearing resistance,
- Fibers of light bulbs,
- tubes,
- special lamps,
- welding electrodes,
- heating resistants of vacuum furnaces for high temperatures etc.

A comparison of metal consumption

Of the global annual production of metal materials, 90% are the Fe alloys, non-ferrous metals and their alloys constitute only 10%.
Around 950 million tons of steel is produced globally per year, out of which approximately 98% is formed steel and the rest are steel castings. Approximately 85% are non-alloy or carbon steels the rest are alloyed steels.
Around 150 million tons of cast iron is produced annually.
The Fe alloys represent the most used materials in engineering, but a big part of the total amount of produced steel is consumed in building industry, where the lowest quality steels are mainly used.
The second most common metal is Al and its alloys, however, the yearly global production is considerably lower in comparison with the Fe alloys – it is estimated to be around 50 million tons.
The yearly global production of Cu and its alloys is around 15 million tons, Zn around 7 million tons, Pb around 5 million tons. The production of other metals does not exceed 5 million tons per year.

2. Aluminum and its alloys

Time to study: 10 hours

Aim: After study of this chapter you will know

- Common aluminum minerals and production of aluminum
- Basic classification of aluminum alloys
- Properties of aluminum alloys and their application

Lecture

[1] Totten, G. E.; MacKenzie, D. S.: Handbook of aluminum. Volume 2, Alloy production and materials manufacturing.

CRC/Taylor & Francis, Boca Raton 2003, 724 s. ISBN 0-8247-0896-2.

- aluminum is one of the most common metals in the nature (around 8% in earth´s crust)
- the basic raw material for the production is bauxite (electrolysis of aluminum oxide in molten fluorides) – energy intensity 14MWh/1t Al

Table 1.1.1. Summary of common aluminium minerals.

Mineral	**Chemical formula**	**Weight % Al_2O_3**
corundum	Al_2O_3	100
diaspore, boehmite	$Al_2O_3.H_2O$	85
gibbsite (hydrargilite)	$Al_2O_3.3\ H_2O$	65.4
spinelle	$Al_2O_3.MgO$	71
kyanite, andaluzite, silamanite	$Al_2O_3.SiO_2$	63
kaolinite	$Al_2O_3.2SiO_2.2\ H_2O$	39.5
alunite	$K_2SO_4.Al_2(SO_4)_3.4Al(OH)_3$	37
nepheline	$(Na,K)_2O.\ Al_2O_3.2SiO_2$	32.3-35.9
leucite	$K_2O.\ Al_2O_3.4SiO_2$	23.5
sericite	$K_2O.3\ Al_2O_3.6SiO_2.2H_2O$	38.4

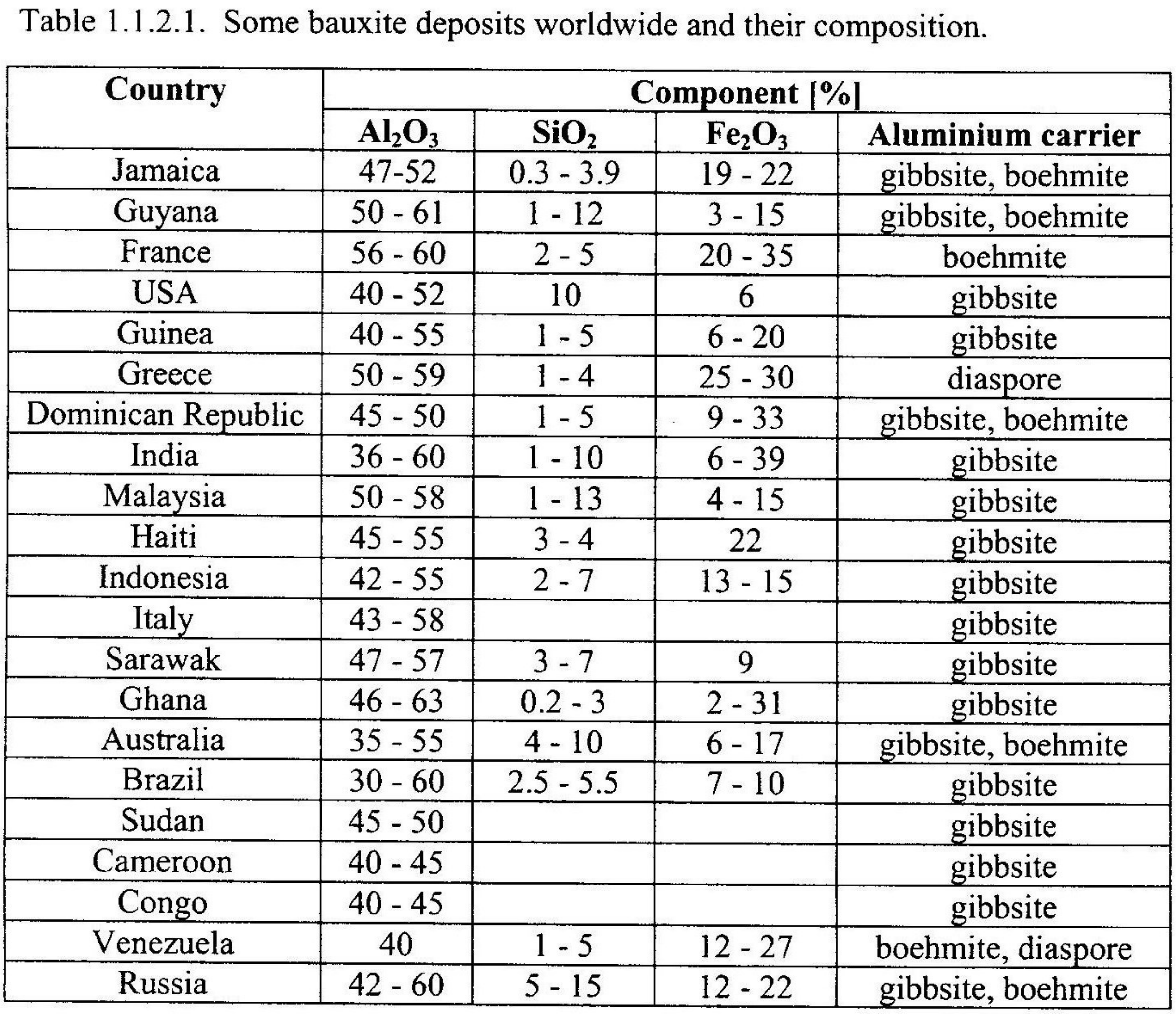


Table 1.1.2.1. Some bauxite deposits worldwide and their composition.

Country	Component [%]			
	Al_2O_3	SiO_2	Fe_2O_3	Aluminium carrier
Jamaica	47-52	0.3 - 3.9	19 - 22	gibbsite, boehmite
Guyana	50 - 61	1 - 12	3 - 15	gibbsite, boehmite
France	56 - 60	2 - 5	20 - 35	boehmite
USA	40 - 52	10	6	gibbsite
Guinea	40 - 55	1 - 5	6 - 20	gibbsite
Greece	50 - 59	1 - 4	25 - 30	diaspore
Dominican Republic	45 - 50	1 - 5	9 - 33	gibbsite, boehmite
India	36 - 60	1 - 10	6 - 39	gibbsite
Malaysia	50 - 58	1 - 13	4 - 15	gibbsite
Haiti	45 - 55	3 - 4	22	gibbsite
Indonesia	42 - 55	2 - 7	13 - 15	gibbsite
Italy	43 - 58			gibbsite
Sarawak	47 - 57	3 - 7	9	gibbsite
Ghana	46 - 63	0.2 - 3	2 - 31	gibbsite
Australia	35 - 55	4 - 10	6 - 17	gibbsite, boehmite
Brazil	30 - 60	2.5 - 5.5	7 - 10	gibbsite
Sudan	45 - 50			gibbsite
Cameroon	40 - 45			gibbsite
Congo	40 - 45			gibbsite
Venezuela	40	1 - 5	12 - 27	boehmite, diaspore
Russia	42 - 60	5 - 15	12 - 22	gibbsite, boehmite

The production of aluminum

Bayer method

$Al_2O_3 + 2\ NaOH$ □ $2\ NaAlO_2 + H_2O$

for gibbsitic bauxites:

$Al(OH)_3 + NaOH\ NaAlO_2 + 2\ H_2O$ ($T_{leaching} > 100°C$)

for boehmitic bauxites:

$AlOOH + NaOH\ NaAlO_2 + H_2O$ ($T_{leaching} > 200°C$)

for diasporic bauxites:

$AlOOH + NaOH + Ca(OH)_2\ NaAlO_2 + Ca(OH)_2 + H2O$ ($T_{leaching} > 240°C$)

The properties of aluminum

Physical properties

- density 2700 kg.m-3
- melting temperature 660°C
- evaporation temperature 2520°C
- face centered cubic crystalline lattice (K12)
- lattice constant a = 4.05.10-10 m
- atomic number 13
- atomic weight 26.98
- thermal conductivity (20°C) 235 $W.m^{-1}.K^{-1}$
- high electrical conductivity (Al 99.99 % at normal temperature it reaches 60% of the electrical conductivity of Cu).

Chemical properties

- aluminum together with oxygen create a very stable Al_2O_3 oxide (the thickness of the layer at normal temperature is up to 10nm)
- in the range of pH 4.5 – 8.5, the chemical resistance is excellent, it is limited in alkaline environment
- at the presence of as little as a few hundredths of Mg, the oxide layer is formed by $Al_2O_3.MgO$ spinels and the protective effect of the layer decreases.

Mechanical properties

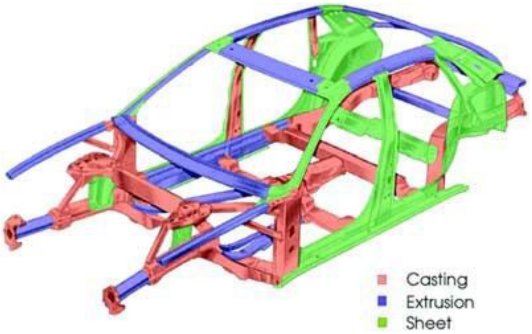
- the mechanical values of pure aluminum are bad – tensile strength – under 100 MPa – hardness – 20-30 HB. Alloying can substantially increase the mechanical values
- plastic properties of aluminum are very good – elongation – above 20%
- pure aluminum is practically impossible to use as a construction material.

Influencing the Al properties

- toughness properties – it is possible to improve them using for example Cu and Mg,
- chemical properties – by alloying using for example Ag, the resistance of some alloys against corrosion under electrical voltage can be increase,
- technological properties – for example, Si improves casting properties, Sc improves weldability,
- physical properties – for example, B improves the electrical conductivity of technically pure Al.

Aluminum applications

Transport (air, water, railway, and car)	59.1 %
Building industry	18.4 %
Engineering	10.3 %
Electrotechnical industry	7.2 %
Food processing industry	4.3 %
Others	0.7 %



Casting alloys of aluminum

Labeling of aluminum alloys for castings according to the ČSN EN 1706

- This norm applies for casting and it specifies the labeling by letters EN AC and five numbers.
- Numerical label may be amended by the chemical one, for example EN AC-21000 [AlCu4MgTi].
- The prefix EN is followed by a space,
- The letter A stands for aluminum,
- The letter C stands for castings,
- hyphen,
- four numbers specifying the chemical composition.

Numerical labeling of alloys

EN AC-XXXXX

X 1 – specifies the main ingredient
(2 - Al-Cu, 3 – Al-Si, 4 –Al-Mg, 5 – Al-Zn)
X 2 – specifies the alloy group and is practically used only in Al-Si alloys
X 3 – is the order number in the group
X 4 and X 5 – are zeros

Division of aluminum casting alloys according to the ASM

- Al-Cu
- Al-Cu-Si
- Al-Si
- Al-Mg
- Al-Zn-Mg
- Al-Sn
- Al-Li

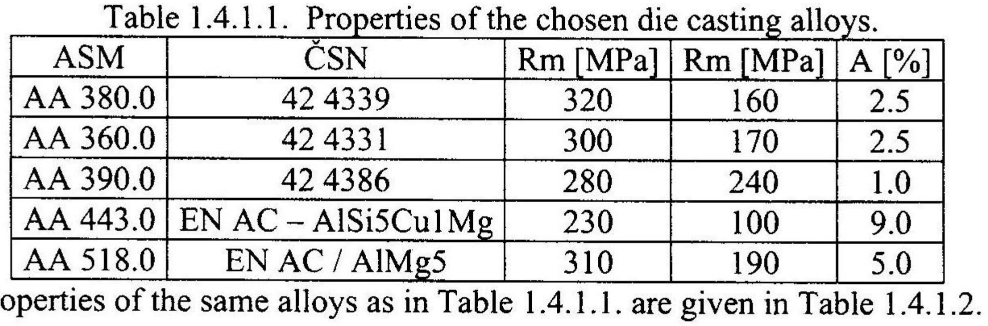


Table 1.4.1.1. Properties of the chosen die casting alloys.

ASM	ČSN	Rm [MPa]	Rm [MPa]	A [%]
AA 380.0	42 4339	320	160	2.5
AA 360.0	42 4331	300	170	2.5
AA 390.0	42 4386	280	240	1.0
AA 443.0	EN AC – AlSi5Cu1Mg	230	100	9.0
AA 518.0	EN AC / AlMg5	310	190	5.0

Physical properties of the same alloys as in Table 1.4.1.1. are given in Table 1.4.1.2.

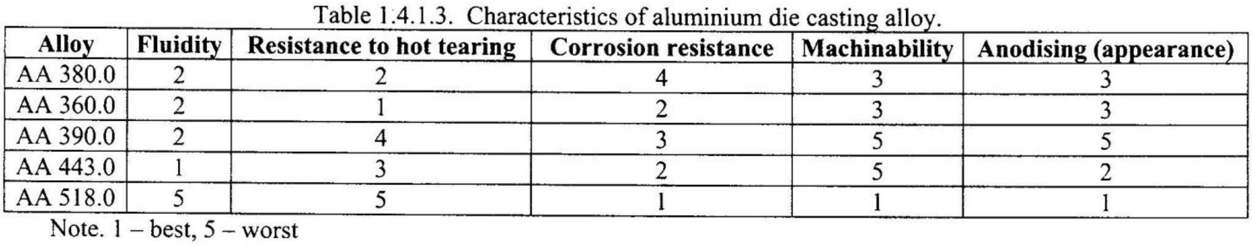


Table 1.4.1.3. Characteristics of aluminium die casting alloy.

Alloy	Fluidity	Resistance to hot tearing	Corrosion resistance	Machinability	Anodising (appearance)
AA 380.0	2	2	4	3	3
AA 360.0	2	1	2	3	3
AA 390.0	2	4	3	5	5
AA 443.0	1	3	2	5	2
AA 518.0	5	5	1	1	1

Note. 1 – best, 5 – worst

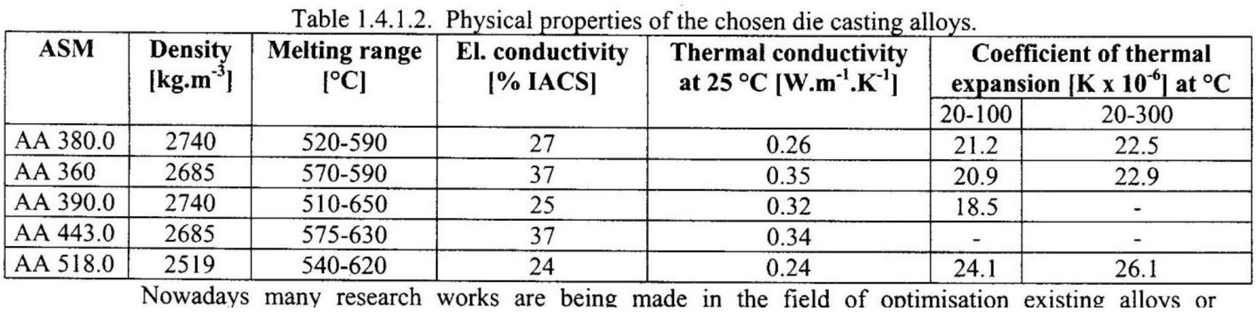


Table 1.4.1.2. Physical properties of the chosen die casting alloys.

ASM	Density [kg.m^{-3}]	Melting range [°C]	El. conductivity [% IACS]	Thermal conductivity at 25 °C [W.m^{-1}.K^{-1}]	Coefficient of thermal expansion [K x 10^{-6}] at °C	
					20-100	20-300
AA 380.0	2740	520-590	27	0.26	21.2	22.5
AA 360	2685	570-590	37	0.35	20.9	22.9
AA 390.0	2740	510-650	25	0.32	18.5	-
AA 443.0	2685	575-630	37	0.34	-	-
AA 518.0	2519	540-620	24	0.24	24.1	26.1

Nowadays many research works are being made in the field of optimisation existing alloys or

Advantages of Aluminum casting alloys

- good castability, which becomes considerably better with increasing share of the given eutectic according to the chemical composition,
- low melting temperature,
- low crystallization range,
- the content of hydrogen in the cast, which is the only soluble gas in aluminum, can be minimized by suitable technological conditions,

- good chemical stability (corrosion resistance),
- good surface properties of the casts,
- for most of alloys, there is a low susceptibility to the formation of cracks at high temperature.

Factors for selecting suitable alloys for making the required casting

1. Casting properties:
- castability,
- resistance to cracking at high temperatures,
- small range of crystallization,
- good properties for die casting.
- Castability is mostly influence by the temperature range of crystallization, the viscosity and the surface tension of the melt
- Resistance to the formation of cracks at high temperatures is in general decreasing with the widening range of crystallization and decreasing strength properties at higher temperatures

2. Required mechanical properties:
- toughness and plastic properties,
- hardness,
- the possibility of increasing the strength properties by heat treatment.

3. Chemical properties:
- corrosion resistance (considerably decreased by the presence of Cu),
- finishing option – anodizing.

4. Properties of final products:
- impermeability of liquids in the casting due to the pressure
- dimensional and thermal stability.

5. Economic factors:
- costs of mechanical processing,
- casting and melting,
- thermal processing,
- castability.

Chemical composition of aluminum alloys

The alloys contain:
- basic element – determines the kind of alloys (aluminum)
- main additive element – crucial for determining the properties of the alloy (in Al alloys Al – Si, Cu,Mg … Zn, Mn)
- minor additive elements – elements that positively influence some of the properties of the given type of alloy
- accompanying elements – elements that were not added to the alloy on purpose

based on the number of additive elements, they are divided into: Binary (basic element and main additive element) ternary and multicomponent.

The influence of alloying elements or impurities

- B – the structure refines, – electrical conductivity is increased in technically pure Al due to the precipitation of V, Ti, Cr, Mo from the solid solution – it increases the ability of Al to capture neutrons.
- Bi – is alloyed for the purpose of improving the mechanical machinability.
- Sb – increases the corrosion resistance in sea water, – decreases the susceptibility of Al – Mg alloys to form cracks at high temperatures, – in bearing alloys it is alloyed by the amount of 4 – 6 %.
- Cr – lowering the susceptibility to grain growth in Al – Mg alloys, – hindering the process of recrystallization in Al – Mg – Si and Al – Mg – Zn alloys, in hardenable alloys it increases the hardenability.
- Cu – increasing the strength properties – by hardening, - decreases the corrosion resistance – most commonly alloyed together with Mg.
- Co – in some Al – Si alloys with the presence of Fe the transformation of needle like phase rich in Fe to a spheric morphology increasing the strength and plastic properties.
- Fe – a common impurity in Al, – the solubility in solid state is low (~ 0.04 %), it is present as an intermetallic compound with Al in the structure – in Al – Cu type alloys, by creating and intermetallic l7FeCu2 phase, there is depletion of solid solution α of copper – decreasing the strength properties – it blocks the grain growth in case of dispersive exclusion of Fe–rich particles in the structure – in Al – Cu – Ni type alloys it increases the strength properties at higher temperatures; and creep.

The properties of Al alloys

Technological properties

- The set of mechanical and physical properties of material, which allows the production of a casting in a defined method
- Among the most important technological properties there are castability, formability, weldability and machinability.
- Machinability – given by a combination of machining forces, the character of particles, the quality of finished surface and the durability of the cutting edge of the machining tools (in Al alloys, the machinability is increased by Cu) – machinability is decrease by hard phases (intermetallic compounds of additive elements and impurities) – influence of Fe
- Corrosion resistance – the ability to resist chemical action of gaseous or liquid environments - in Al-Si alloys the relatively good corrosion resistance is decreased by Cu
- Weldability - the ability of connecting using various welding technologies and the reachability of the strength and quality of connections
- Polishability and the possibility of finishing – the ability of surface processing of the castings - in Al alloys, the anodic oxidation is common
- Impermeability – the ability to prevent the pressurized media (gas, liquid) from coming through the walls of the casting → stress tests – the tightness is mainly related to the occurrence of cracks and or microshrinkages

Casting properties

- fluidity – the ability of the liquid metal to fill the mold cavities – it depends on the size of the solidification range of the given alloys – e.g. eutectic alloys (narrow solidification interval) → good fluidity – the influence of surface tension, wettability of the form, modification
- tendency to shrinkages – the volume decrease of the metal during the solidifying and the tendency of creation of concentrated (inner and outer) shrinkages and shrinkage porosities
- tendency to gassing – characterized by the solubility of gases in liquid state, the level of gassing determines the formation of gas bubbles
- resistance to the formation of cracks – the ability to withstand the stresses at the solidifying temperatures range and during the cooling

Mechanical properties

- Depends mainly on the type and properties of the main metallic matter, on the dispersity of the structural components, on the presence and shape of intermetallic phases and on the heat processing,
- Fine-grained structure clearly improves all the mechanical and a number of technological properties of alloys,
- The following are monitored especially: tensile strength at normal temperature, yield strength (limit $Rp_{0.2}$), elongation and hardness, properties at high temperatures.
- Limit strength – Rm – in Al alloys – 150 to 250 MPa – after hardening (alloys with the addition of Cu, Mg) – increase by 30 to 50% → 330 MPa
- Elongation - 1 – 4 %, an increase can be reached by the modification of the eutectic

- hardness – at the cast state in Al-Si : 60 – 80 HB, after hardening – 100 HB
- quality index – determined by tensile strength and elongation: Q = Rm + k.log A5 (MPa)

Selected binary diagrams aluminum - alloys

For example, the melting temperature of aluminum has been gradually specified during the years to the present value of 660.452°C (for the super-pure aluminum - 99.9995 % Al), which is closely related with the purity of aluminum.

Aluminum with 99.2 to 99.5 % Al content has the melting temperature in the range 657 to 658 °C.

Purer aluminum with 99.6 % Al content melts at 658.7 °C and the aluminum with 99.97 % Al content has the melting temperature of 659.8 °C.

Later measurements for pure aluminum with 99.996 % Al content indicate the melting temperature of 660.24 °C, in other words 933.4 K.

The most common binary solutions of aluminum: e.g. Al – Cu, Al – Mg, Al – Mn, Al – Si, Al – Zn. In these systems, aluminum creates a substitutionary solid solution with correspondent elements. This solution has good formability and toughness and also better mechanical properties than pure aluminum.

The maximum solubility of additive elements in the solid solution of Al is at the eutectic temperature.

With decreasing temperature, the solubility of additives decreases and at room temperature, it is usually small or even negligible.

-it is possible to perform heat treatment – hardening

-hardenable and unhardenable alloys

Equilibrium binary diagrams are usually of simple eutectic or peritectic type on the aluminum side.

At higher concentrations of additive, the diagrams are complicated by the formation of intermetallic phases (additives like Cu, Mg, Mn) or they are just simple diagrams with limited mutual solubility of both components in the solid state (system Al - Si).

The diagrams are divided into four basic types:

- P type – peritectic – the additive increases the melting temperature of Al,
- E1 type – eutectic – the additive decreases the melting temperature of Al and in solid solution, the Al is well soluble,
- E2 type – eutectic with limited solubility of additives in the solid solution of Al,
- M type – monotectic – the reaction takes place with composition similar to the pure Al.

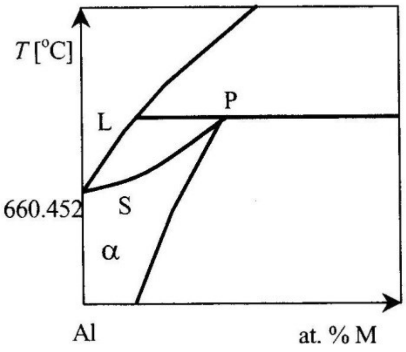
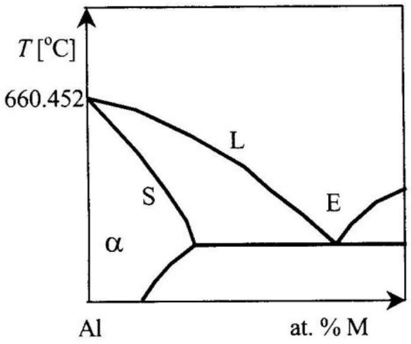
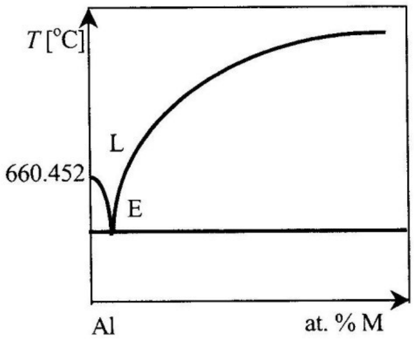
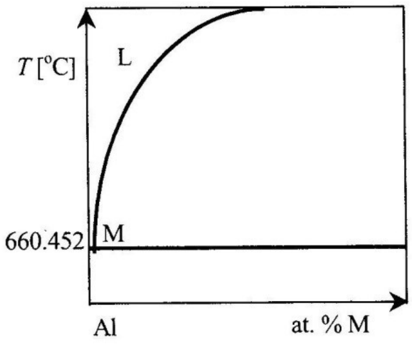
Al - M Binary Diagram	**Type**	**Admixture M**
	**P** **Peritectic** $k_o > 1$	Cr, Hf, Mo, Nb, Ta, Ti, V, W, Zr
	**E1** **Eutectic** $k_o < 1$	Ag, Au, Be, Ca, Ga, Ge, Hg, Li, Mg, Si, Sn, Th, Zn
	**E2** **Eutectic with very small solubility in solid** $k_o < 0.01$	B, Ba, Bi, Cd, Ce, Co, Dy, Er, Eu, Fe, Gd, H, Ho, In, Ir, La, Lu, Mn, Nd, Ni, Pb, Pd, Pm, Pr, Pt, Pu, Ru, Rh, Sb, Sc, Sm, Sr, Tb, Te, Tm, U, Y, Yb
	**M** **Monotectic**	As, C, K, N, Na, P, S, Se, Tl
	$k_o < 0.001$	He, Ne, Ar, Kr, Xe, Rn

Fig. 2.7.1. Standard types of binary diagrams of the aluminium – admixture systems.

Intermetallic phase in the Al alloys

Table 2.7.2. Intermetallic phases in binary alloys on the basis of aluminium and their characteristics [3].

Intermetallic phase	Type of structure	Number of atoms in elementary cell	Density [kg.m^{-3}]	Melting temperature [°C]
Ag_2Al	hexagonal	2	8140	730*
$\alpha - AlB_{12}$	monoclinic	52	2530	
$\beta - AlB_{12}$	tetragonal	208	2580	~1350
AlB_2	hexagonal		3170	~850*
$CaAl_4$	tsc	10	2330	700*
Co_2Al_9	monoclinic	22	3600	1940
$CrAl_7$	rhombic	1160	3140	~725*
$CrAl_{11}$	rhombic	1209	3340	~940*
$\theta - CuAl_2$	tsc	12	4350	590
$\theta' - CuAl_2$	tetragonal	6	4120	
$\theta'' - CuAl_2$	tetragonal	8	3830	
$FeAl_4$	monoclinic	~100	3780	1160*
$FeAl_6$	rhombic	42	3450	
$AlLi$	fcc	16	1730	717
Mg_2Al_3	fcc	1166	2230	450
$MnAl_6$	rhombic	28	3310	710*
$MnAl_4$	hexagonal			820*
$MnAl_{12}$	cubic			
$NiAl_3$	rhombic	16	3960	855*
Ni_2Al_3	hexagonal	5	4760	1130*
$NiAl$	bcc	2	5910	1640
$AlSb$	cubic - diamond	8	4340	~1050
$TiAl_3$	tsc	8	3370	1340*
UAl_4	rhombic	20	6060	730*
VAl_{11}	fcc	12	2980	670*
VAl_6	hexagonal	56	3200	740*
$ZrAl_4$	tsc	16	4110	1580
TiB_2	hexagonal	3	4500	2790
$\beta - Mg_2Si$	fcc	12	1990	1100
Mg_2Zn_{11}	cubic	39	6120	385*
$MgZn_2$	hexagonal	12	5200	590

Notes: tsc – tetragonal space-centred, * - phase formation through peritectic reaction

Al – Cu type alloys

The content of Cu is usually in the range of 4 – 5 %. Their strength properties can be increased compared with cast state by heat treatment.

Alloys with Cu content of 9 – 11% are also produced, and they have good strength properties at higher temperature and also good abrasion resistance.

Adding Ni and Mg helps in achieving very good strength properties at higher temperatures.

The disadvantage of these alloys is the worse castability and low corrosion resistance.

The examples in Czech norms are these alloys:

- AC – AlCu4MgTi (4.2 – 5.0 % Cu, 0.15 – 0.35 % Mg, 0.15 – 0.35 % Ti)
- AlCu4Ni2Mg2 (3.75 – 4.5 %Cu, 1.75 – 2.25 % Ni, 1.25 – 1.75 % Mg)

Al – Cu – Si type alloys

These are extensively used alloys, in which the castability properties have been improved compared to the first type by adding Si.

In these alloys, Cu or Si is predominant. The alloys with Cu content above 3 % are heat treatable. Mostly, only alloys, which also contain Mg are heat processed. Alloys with high content of Si (above 10%) are applied when a low coefficient of thermal expansion is required. Alloys that contains up to 22% of Si have a high abrasion resistance.

According to ČSN, the following alloys are available:

- ČSN 42 4339 - AlSi8Cu2Mn alloy (7.5 – 9.5 % Si, 2 – 3 % Cu, 0.3 – 0.5 % Mn)
- ČSN EN 1706 - AC-AlSi6Cu4 alloy (5.0 – 7.0 % Si, 3.0 – 5.0 % Cu)
- ČSN 42 4386 - AlSi20Cu2NiMgMn alloy (19.0 – 22.0 % Si, 1.5 – 2.0 % Cu, 0.5 – 1.0 % Ni, 0.8 – 1.2 % Mg, 0.1 – 0.4 % Mn).

Al – Mg type alloys

They have a very good corrosion resistance especially in sea water. Alloys made of highly pure materials exhibit the best corrosion resistance. They are weldable and also have a good mechanical machinability. When applied in architecture, there is possibility of anodizing the casting.

The disadvantage of these alloys is their bad castability and susceptibility of magnesium to oxidation during the process of melting.

The following are the examples of these alloys:

- ČSN 42 4515 - AlMg5Si1Mn alloy (4.40 – 5.50 % Mg, 0.60 – 1.50 % Si, 0.25 – 0.6 % Mn)
- ČSN 42 4519 - AlMg10SiCa alloy (7.00 – 10.00 % Mg, 0.01 – 2.00 % Si, 0.01 – 0.15 % Ca)

Al – Sn type alloys

They are alloys with approx.6 % content of Sn and a small amount of Cu and Ni (with the aim of increasing the strength properties). They are especially intended for manufacturing of slide bearings.

From the casting point of view, the main problem is the wide range of crystallization and the possibility of segregation of Sn.

In ČSN, there is no available representative of this type of alloys. In American norms, we may find the alloy labeled AA850.0 – 6.5Sn-1Cu-1Ni.

Al – Si alloys

They are applied when good castability and corrosion resistance are required.

The amount of Si in these alloys usually varies between 5 and 13 %. According to the amount of silicon they are divided into under-eutectic (less than 12 % Si), eutectic (around 12 % Si) and over-eutectic (more than 12 % Si).

In cases where Mg is not alloyed, there is a possibility of heat treatment of these alloys and they are not alloy by copper.

According to ČSN, SN 42 4330 is available - AlSi12Mn alloy (11.00 – 13.00 % Si, 0.1 – 0.4 % Mn).

The industrial importance of Al – Si is given by their high fluidity, low susceptibility to the formation of shrinkages during casting and the possibility of welding and soldering.

Solid particles of silicon increase the resistance to abrasion.

„Modified" alloys (with small additions of 0.01 wght.% Na, Sr or P) considerable improve the microstructure (refinement of Si particles in under-eutectic alloys) and the mechanical properties of binary alloys.

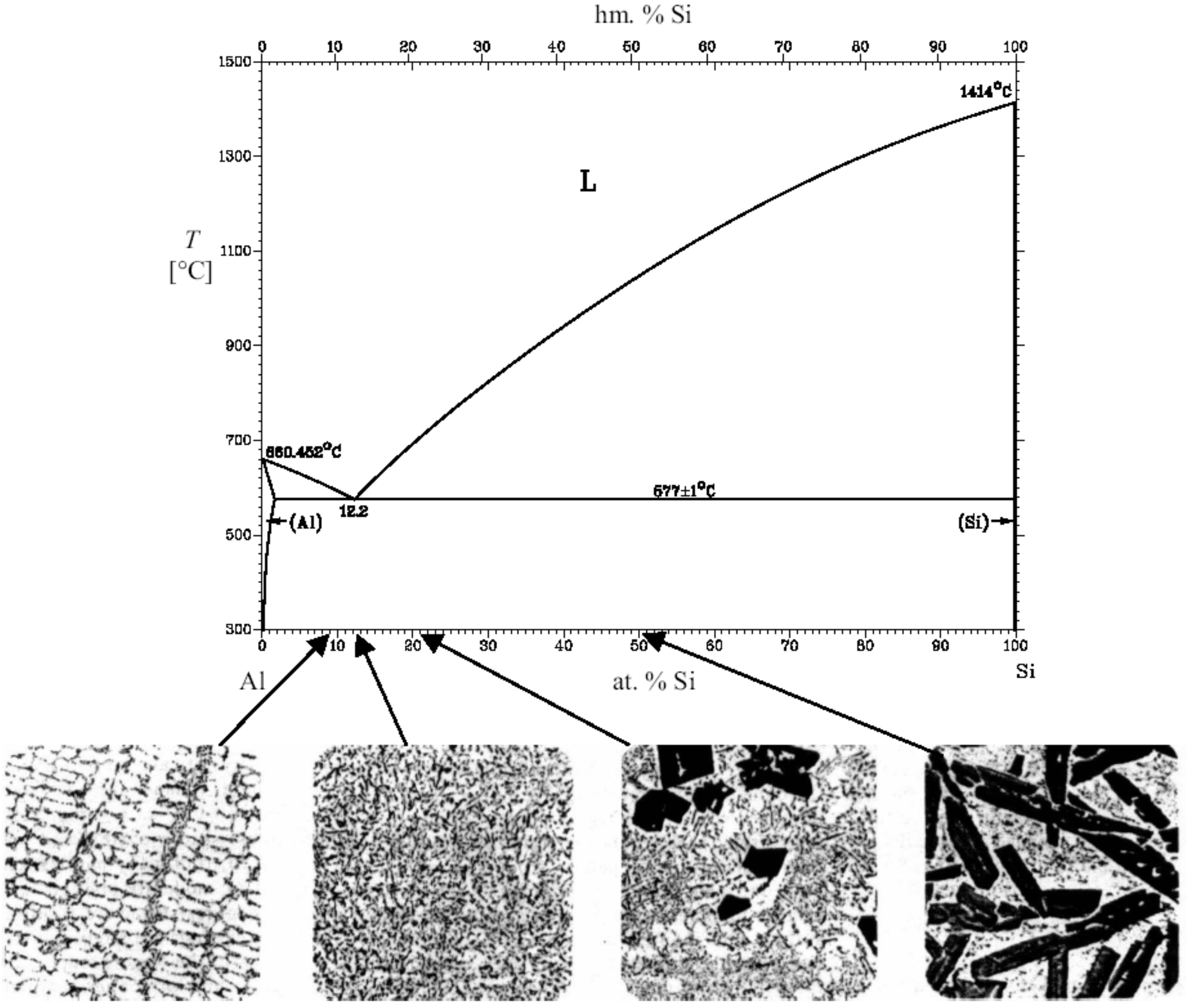
Cu or Mg may also be added to Al – Si alloys with the intention of hardening by aging.

Aluminum – silicon diagram

Silicon has a very limited solubility in aluminum at the eutectic temperature the solubility is only 1.65 % Si and it continues to decrease with decreasing temperature.

In foundry alloys, the amount of silicon is always higher than the maximum solubility in solid solution α(Al), that is why they always contain α(Al)-Si eutectic.

Eutectic concentration of silicon is 12.5 % Si (according to some sources only 11.7 % Si), eutectic temperature is 577°C.



8 at. % Si　12 at. % Si　20 at. % Si　50 at. % Si

Eutectic is a mixture of α-phase and eutectic silicon created by an eutectic transformation. It is formed by eutectic cells.

Eutectic cell is a crystalline unit formed during the eutectic transformation. Eutectic phases are continuously excluded in the eutectic cells.

A characteristic feature of these eutectics is the invisible interface between cells.

The division of silumins according to the content of silicon

- Under-eutectic – the structure is created by a network of primary dendrites of the α(Al) phase and the eutectic that is excreted in the interdendritic spaces. With the increasing amount of Si, the amount of eutectic also increases. Under-eutectic alloys contain more than 5% Si, most commonly between 7 and 11 % Si.
- Eutectic alloys – contain approximately 11.5 – 13 % Si. Their structure is formed only by the eutectic, sometimes (especially in modified alloys), the single α(Al) phases also occur.
- Over-eutectic silumins – contain particles of primary silicon and the eutectic. The usual content of Si in over-eutectic silumins is around 14 – 17 % Si, in some cases even up to 25 % Si.

Morphology of the eutectic in Al-Si alloys

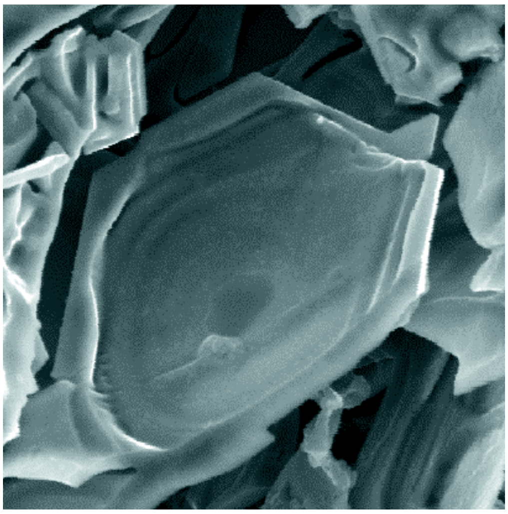
The type of eutectic is linked to the mechanism of crystallization of eutectic silicon.
The particles of aluminum phosphide AlP serve as the crystallization nuclei. Phosphorus gets into the melt as an impurity especially from the raw materials, but also from the used metallurgical products and salts, or from lining materials.
To create a sufficient quantity of the nuclei, its amount in the melt has to be only several ppm units of phosphorus (1 ppm = 0.0001%).

Silicon is excreted in the Al-Si alloys as a pure elements with minimal content of other additives. The size of particles of eutectic silicon can be in the range from less than 1 μm up to more than 2 nm. It may occur in three distinct forms in the eutectic.
The type of eutectic is named after the shape of silicon particles:
- granular
- lamellar
- modified

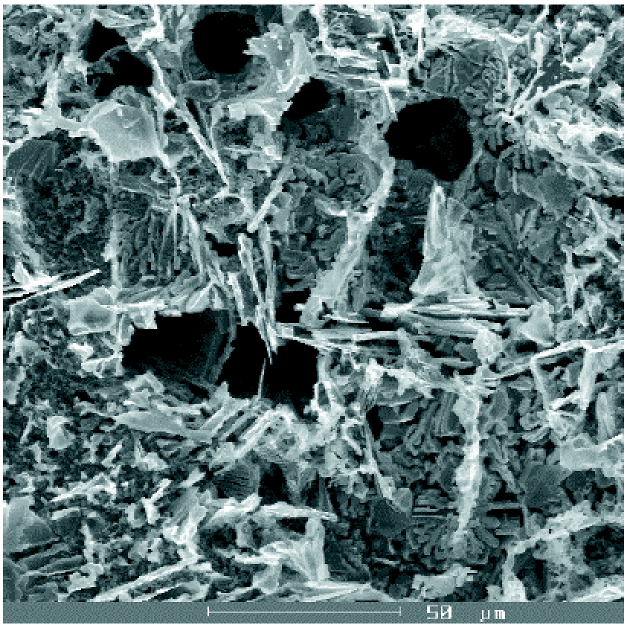
Eutectic present in the unmodified Al-Si alloys is a two-phase structure consisting of α-phase dendrites and plates of eutectic silicon with different orientation, which in metallographic section appears as gray needles stored in bright α-phase matrix.

The distribution of plates of eutectic silicon in the unmodified eutectic can be of two types.
- The first type of distribution represents a non-oriented distribution of plates of eutectic silicon, which is labeled by foreign authors as granular eutectic.
- The second type of distribution represents a fan-shaped (straight or angled) distribution of plates of eutectic silicon, labeled by foreign authors as lamellar eutectic.

Granular eutectic – is formed when the content of phosphorus is above approx. 5 – 10 ppm – eutectic silicon is excreted in the shape polyhedral grains or thick lamellae.



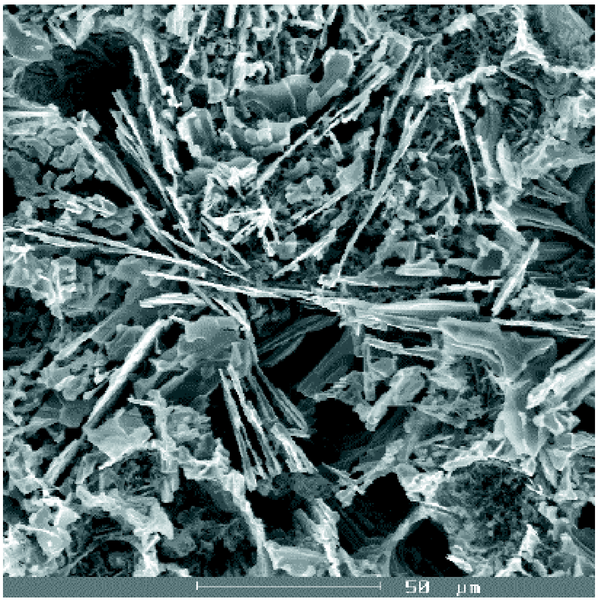
The spatial shape of hexagonal plate of non-modified eutectic silicon in the AlSi10MgMn alloy, deeply etched by the etchant, Aachen REM.



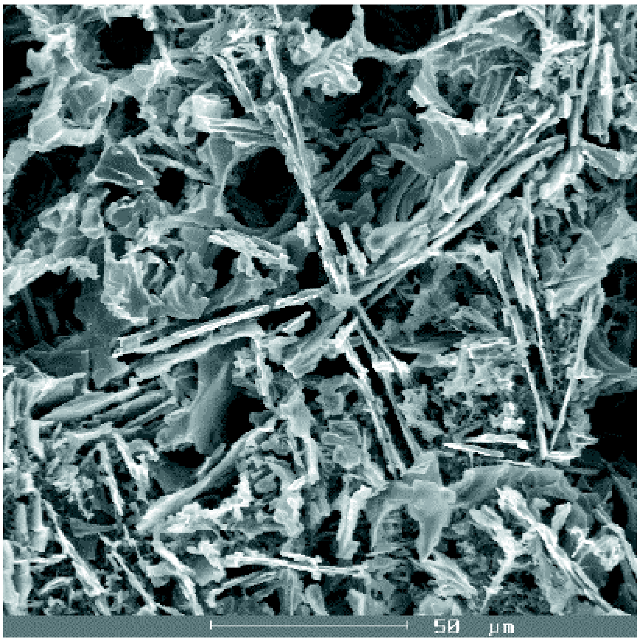
Non-oriented distribution of silicon plates in the AlSi10MgMn alloy– non-modified eutectic Si

Lamellar eutectic – formed in pure alloys with very low content of sodium and a content of phosphorus approximately 1-2 ppm. The conditions for nucleation of lamellar silicon are less suitable (smaller content of phosphorus gives smaller number of nuclei), it crystallizes the lamellar eutectic at higher supercooling under the equilibrium eutectic temperature – approximately 2 – 5 K.

Silicon creates fine lamellae, arranged next to each other in more or less parallel manner. The eutectic grains are considerably smaller than in granular eutectic. This type of eutectic also occurs in alloys modified by the following elements – arsenic, antimony, selenium or cadmium.



Fan-shaped angled orientation of silicon plates in the AlSi10MgMn alloy – non-modified eutectic Si

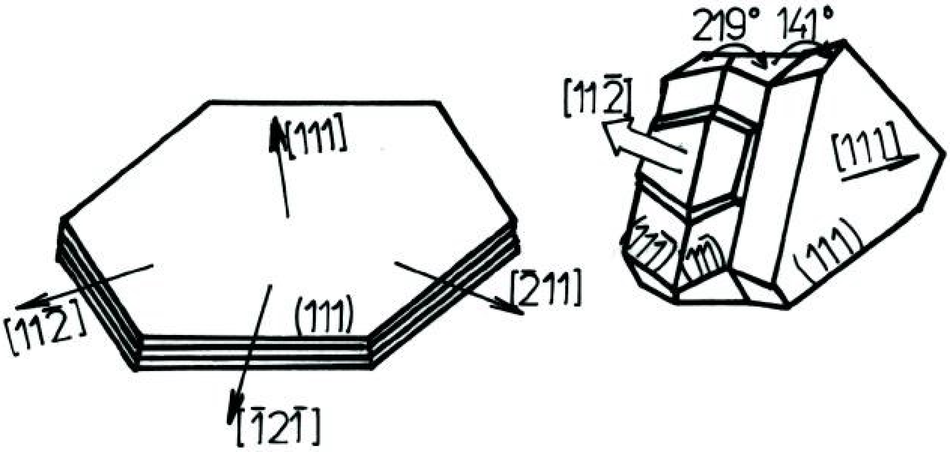


Fan-shaped direct orientation of silicon plates in the AlSi10MgMn alloy – non-modified eutectic Si

The structure and properties of casting alloys can generally be influenced by changes in the liquid metal. These changes consist of adding a small amount of appropriately selected substance, which influences the process of crystallization. One of these changes of liquid metal is modification, which is used to influence the method of growth of crystalline nuclei resulting in morphological changes in excreted phases.

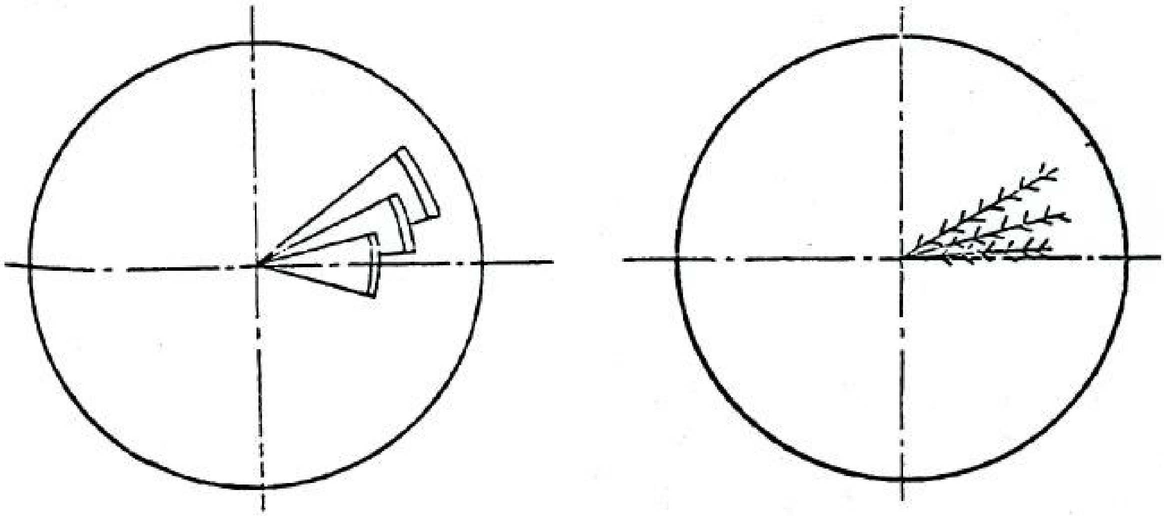
Modified eutectic – is formed in the presence of modification elements (especially Na and Sr), sodium has the strongest modifying effect, rare earth metals, for example, and have a weaker modifying effect.

The effectivity of the modifier depends on the density of twins in the particles of silicon. Sodium has the smallest distance of twinning layers, and that is why its effect is the strongest.



a) multiple twinning in hexagonal crystal of silicon
b) preferential crystal growth of silicon in the direction of <211>

The silicon crystals surface in the modified alloy is rough due to the multiple layers of twinning. The particles of Si are crystallicaly imperfect and each crystalline error is a potential location of another branching.



Schematic representation of eutectic silicon growth model
a) unmodified eutectic silicon
b) modified eutectic silicon

The degree of modification depends also on the cooling rate.
At high cooling rates of casts, it is easier to obtain a fine, well modified structure even when using weaker modifying elements (Sr).
At low cooling rates, for example, in the case of thick-walled casts that are cast into sand molds, only strong modifiers are effective, especially sodium.

Casting silumins contain a high content of eutectic, or their structure may be purely eutectic. Therefore, the properties having influence over the mechanical properties of the casts are the properties of the α-phase and the amount, morphology, size and distribution of the eutectic silicon. In Al-Si alloys, modification is used for obtaining the optimal shape of eutectic silicon.

The shape of eutectic silicon (hexagonal plate, in the plane of the needle cut with a sharp ending) in a non-modified eutectic of the Al-Si alloys considerably decreases the mechanical properties of the silumin. This is the reason for performing the modifying of these alloys that results in considerable change of structure and excretion of eutectic silicon in the form of small bar, or even almost fibers, which appear to be rounded grains in the metallographic cut plane.

The excretion of eutectic silicon in the shape of bars or even fibers causes an increase in mechanical properties of modified Al-Si alloys compared to unmodified Al-Si alloys.

The change of shape of the eutectic silicon by modifying from a plate to a bar or even a fiber increases the tensile strength Rm, plastic mechanical properties (A5, Z) and toughness. The change of yield strength Re depending on the process of modification has not been found.

Al-Si alloys modifiers

Sodium

- Is among the most commonly used modifiers.
- Sodium is included in pure state in the form of NAVAC – patron (FOSECO company, duration of the effect 30 min.), or in the form of salts, e.g. T3 (duration of the effect 10 to 15 min.), COVERAL Ep 3275 (duration of the effect 120 to 160 min.) and others. The duration of the sodium effect ranges from 10 to 30 minutes, in some exceptions (only in excellent kinds of modified products based on sodium) 1 - 2 hours.
- Sodium same as other surface active elements (e.g. Sr), causes the delay of crystallization of eutectic silicon resulting in a decrease of eutectic transformation temperature to 569°C and the eutectic transformation move from 1.3 % Si to 14 % Si.
- The following disadvantages have been found in the practical use of sodium and its salts: - sodium increases the degree of gasseation of silumins – the alloy modified by sodium cannot be degasses, filtered, etc. because the effect of modification vanishes – sodium increases the coefficient of volume shrinkage in the interval of alloy hardening, resulting in an increased occurrence of diffused porosity - the quick blast of sodium complicates its dosage in the conditions of serial production.
- The mentioned disadvantages made it necessary to find other modifiers and testing their influence on the structure and properties of the silumins.

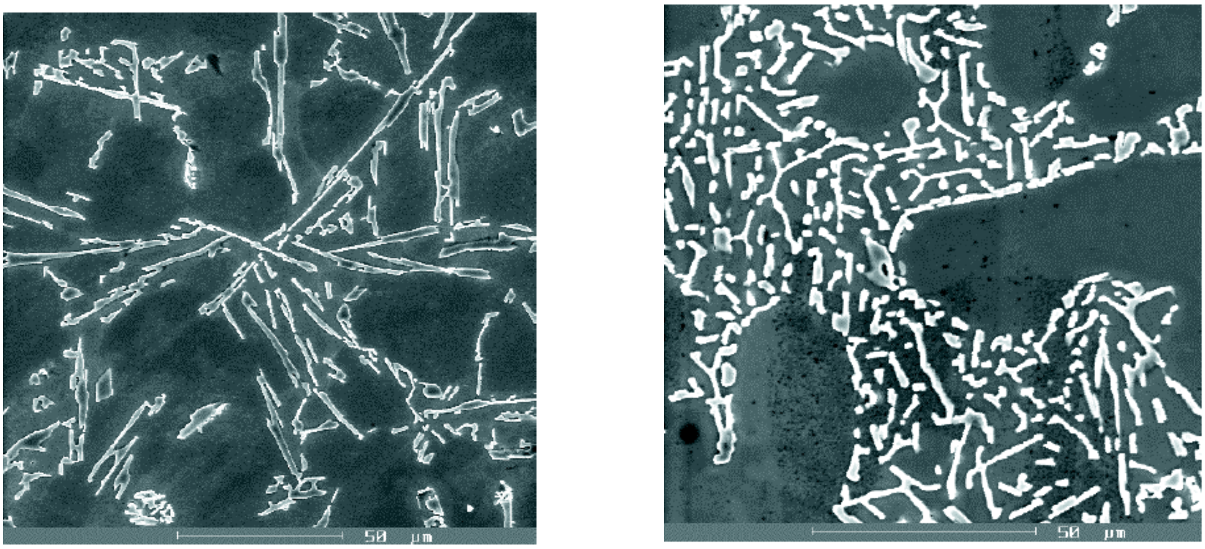
Strontium

- Is a more and more used modifier in under-eutectic and eutectic silumins
- Its modifying effect is longer (1 to 2 hours.), and the time of effect can be prolonged to up to 10 hours by the addition of 0.05 % to 0.2 % beryllium, which decreases the oxidation rate of the melt and thus stabilizes the effect of strontium
- Another advantage is a smaller decrease of the eutectic transformation temperature
- strontium is inserted in the form of pre-alloy, e.g. AlSi13Sr10, AlSi16Sr10, AlSr5, AlSr10, or in the form of SrCO3. Pre-alloys of the AlSr type contain Sr in the form of particles of the Sr Al4 type.
- The amount of pre-alloy has to be calculated for the optimal amount of pure strontium that reaches 0.03 to 0.06 % and depends on the cooling rate of the casting and on the content of silicon in the alloys.
- When exceeding the optimal amount, brittle phases of Al2Si2Sr type are formed and excreted in the segregation areas
- The mechanism of modification by strontium consists of the following reactions – decay of SrAl4 particles in the melt – formation of new particles of the Al2Si2Sr phase – repeated decay of particles of the Al2Si2Sr phase while forming free Sr – the influence of free Sr on the method of silicon crystal growth in consistence with the theory of influence of the

surface active elements – partial reaction of Sr with phosphorus (contained in the alloy in form of impurity from raw materials) while forming strontium phosphides leading to suppressing the modifying effects of strontium.

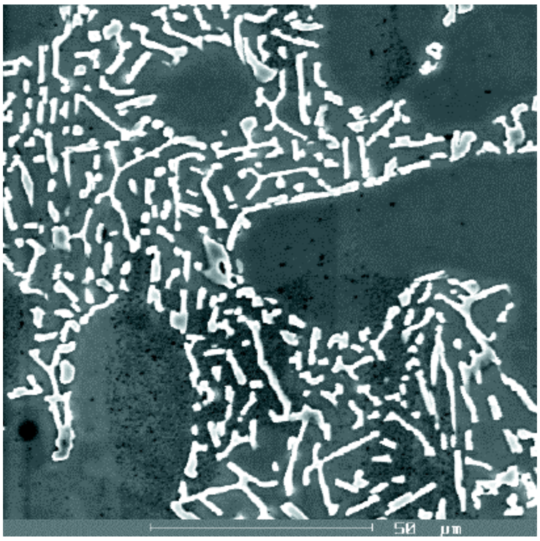
- The kinetics of these reactions is considerably influenced by the rate of decay of the SrAl4 particles and the reaction between strontium and phosphorus. The rate of decay of the SrAl4 particles depends on the size
- For the pre-alloys contain small particles of SrAl4 with dimensions of 1 - 10 µm the speed of their decay is quite high and the optimal modification effect is reach after 2-5 minutes from the insertion of pre-alloy in the melt
- For the pre-alloys containing bigger particles of SrAl4 with dimensions of 10 - 130 µm or 100 - 400 µm the speed of their decay is slower and the optimal modification effect is reach in 10-30 minutes
- The reaction between strontium and phosphorus causes the suppression of the modifying effect of strontium and it begins to take place after 10 minutes from insertion of the pre-alloy containing strontium
- This reaction causes the bonding of part of the strontium from the pre-alloy on the strontium phosphides. That is why the modifying effect is not of the same size that would be reached if this reaction did not happen
- After finishing the reaction between strontium and phosphorus, the modification reaction may continue with the remaining amount of strontium that was not consumed to form strontium phosphides
- When modifying by the pre-alloys containing strontium, it is necessary to select the period of modification reaction up to 10 minutes, when the reaction between strontium and phosphorus has not yet begun

Morphological scale of eutectic silicon, modification of under-eutectic silumin AlSi10MgMn by strontium - REM

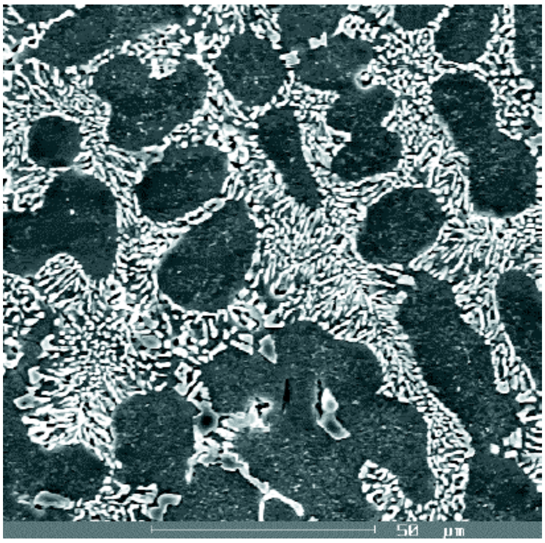


0% Sr

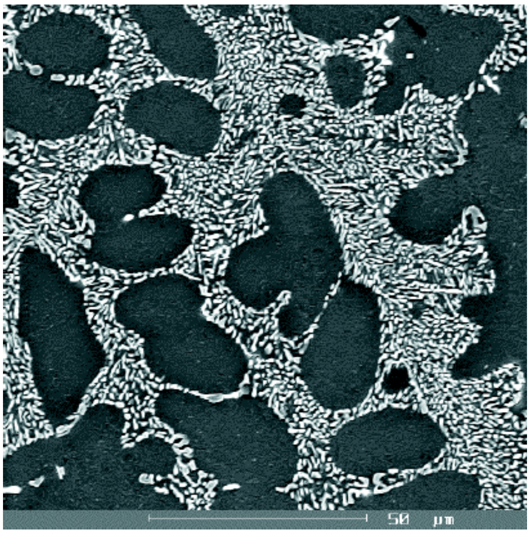
0.01% Sr



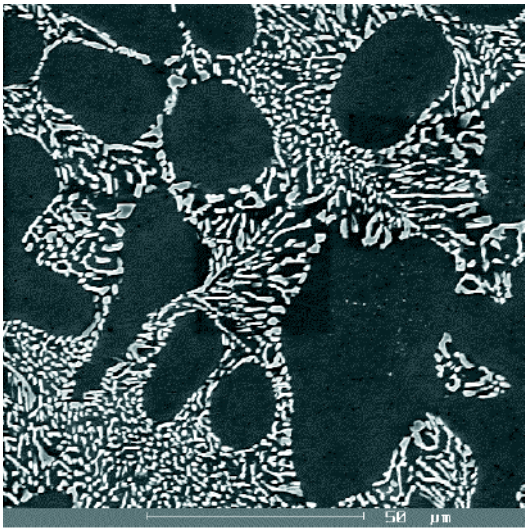
0.02% Sr



0.03% Sr



0.04% Sr



0.05% Sr

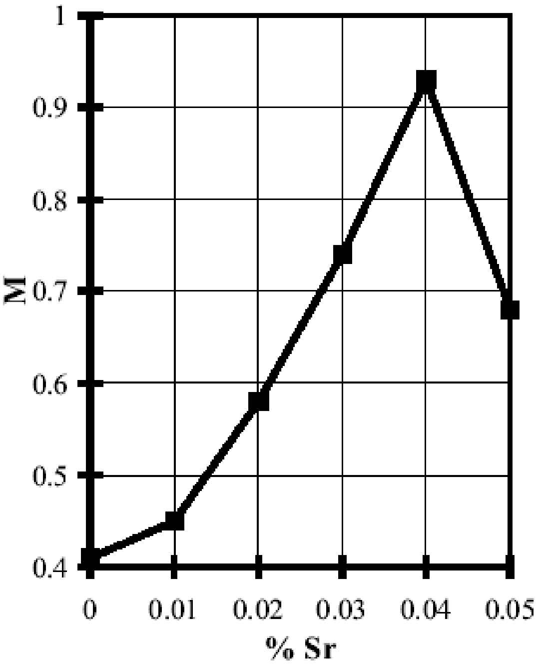
Quantitative evaluation of eutectic silicon morphology

Using the median of the shape factor M, which has proven well as a descriptor when evaluating the shape of graphite in alloys and is defined by the following relation:

$M = 4\pi P/B2$

where P is the surface of the particle and B is the perimeter of the particle

The change of values of the shape factor M of the eutectic silicon correspond fully to the shape changes of eutectic silicon in the whole modification range and at optimally modified state, (0.4% Sr) they reach the value of M factor maximum.



- Under-modified eutectic silicon is characterized by imperfect transformation of Si hexagonal plate to a bar or fiber. In the plane of metallographic section, the bodies of such particles of eutectic silicon exhibit by rounding the edges of needles of eutectic silicon and local occurrence of grains, which represent a cut by the plane of section through imperfectly modified bodies of eutectic silicon.
- With the rising amount of Sr, the portion of needles of eutectic silicon with rounded edges decreases and the proportion of grains, which start to gain rounded shapes, increases. These correspond to the cut of the plane of the section through the particles of eutectic silicon that starts to resemble the bodies of bars and fibers.

Al-Si alloys modifiers

Phosphorus

- Is suitable as a modifier for over-eutectic silumins, it is not used for under-eutectic and eutectic silumins
- In unmodified state, the casting structure of the over-eutectic silumins is composed of rough crystals of primary silicon and the eutectic (α+Si), in which the silicon is precipitates as coarse plates that are visible on the metallographic section as needles
- Phosphorus and aluminum create aluminum phosphide AlP with high melting point, which serves as an active pad during crystallization of the primary Si.
- Phosphorus also increases the strength of bonding forces of silicon atoms, by which it helps to create the pre-crystalline groups of silicon atoms in the melt, controlling the process of crystallization of the primary silicon
- The additives of phosphorus do not influence the eutectic silicon
- When modifying by sodium and phosphorus at the same time, the formation of sodium phosphides Na_3P occurs, because the affinity of phosphorus to sodium is greater than to the aluminum. The influence of both elements is thus cancelled resulting in non-modification of the primary precipitated Si and non-modification of eutectically precipitated Si as well

- This problem is solved by two-level modification. First, the $NaPO_3$ is added to the alloy and sodium is added later at lower temperature
- The result of such modification exhibits by the small precipitation of primary silicon and change in morphology of the eutectic silicon, leading to increase in mechanical properties
- Phosphorus is inserted in the form of CuP10 pre-alloy, or in the form of additives releasing phosphorus, such as NUCLEANT 10 or pentacloride PCl5, which also releases Cl2 and therefore acts as a degassing agent

Calcium
- Is highly debated element and the opinions about the modification by calcium differ
- Some authors claim, that Ca suppresses the modification effect of Na and Sr and causes the occurrence of rough particles of eutectic silicon. These rough particles correspond more to the pre-modified eutectic.
- This fact is confirmed by the opinions of most of authors and it shows that Ca has a modification effect and that in combination with Na and Sr it can cause premodification structures
- That is why it is recommended to keep the maximum content of Ca in alloys up to 0.001%

The combined effect of Na, Sr, P and Ca is not complexly explored and there are only sporadic attempts at explaining the mutually modified influence of elements Sr-P and Ca-Na-Sr, or Na-P.
The results of these works indicate that when modifying the Al-Si alloys with sodium or strontium, it is necessary to keep the content of Ca and P under the limit of 0.001% and the elements like Ca and P are not used normally as modifiers (with the exceptions of phosphorus in over-eutectic silumins).

During the combined use of Na, Sr, P and Ca, there was a decrease in mechanical properties (especially in ductility), which can be caused by overmodifying the structure.
A modifying effect on Al-Si alloys has been observed also for some other elements:
- Tellurium in the amount from 0.04 to 0.4% has a permanent modifying effect, but in alloys with silicon content of more than 13% there is no increase in mechanical properties
- Barium has a very similar effect as strontium and it can also be stabilized by a small adition of beryllium
- Sulfur is recommended to modify in the amount of 0.01 to 0.02 %
- Antimony in the amount of 0.1 to 0.2 % has a similar effect as sodium (but has a less pronounce effect on the structure and it is suitable as a modifier only during chill casting, and it is necessary not to let sodium get into the addition)

Al alloys

Vaccination

- Adding a small amount of suitably chosen substance which affects the process of crystallization (vaccination), which primarily influences the number of crystallization nuclei and it results in softening the structure.

- One of the most important parameters, which determine the properties of aluminum alloys is the size of primary phase.
- Every grain is formed by several dendrites, which grow out of a single crystallization nucleus. The size of grains is usually between 1-10 mm in aluminum alloys.
- They are primarily Al-Cu alloys (which contain only the primary phase) and Al-Si alloys with lower content of an eutectic. With the rising content of silicon, the content of an eutectic is increased, therefore the influence of eutectic silicon is more prevalent and the influence of primary phase dispersity is lower.
- Vaccination is especially effective in sub-eutectic siluminates with high fraction of solid solution α in their structure, i.e. in Al-Si alloys with silicon content of 5-7%.
- During intense cooling (thin-walled casts and casts poured into metal forms), a high overcooling of melt occurs under the equilibrium temperature of crystallization, at which less suitable nucleation appears. This results in obtaining soft-grain structure without any metallurgical intervention.
- Durin the casting with thicker walls of the casts and especially in casting into sand forms, the intensity of cooling is substantially lower and therefore the alloy has a coarse-grain structure.

There are several theories to explain the softening of the phase:
- a theory based on peritectic transition in the system of aluminum-transition metal
- a theory based on the formation of intermetallic compounds of aluminum and transition metal, or the transition metal carbide.
- a theory stemming from the electron structure of transition metals where the softening effect of the metal is stronger if there are less electrons on the d-orbital of its atoms

The principle of vaccination of Al-Si alloys

- The softening of a solid solution is performed by adding Ti and B, which are introduced into the melt individually or combined. These elements are introduced into the melt in form of intermetallic compounds, which are contained in the corresponding pre-alloys.
- Titanium is introduced into the melt by adding the pre-alloy type AlTi (such as AlTi6), which include the intermetallic compound $TiAl_3$.
- Boron is introduced into the meld by adding the pre-alloy type AlB (such as AlB4), which include the intermetallic compound AlB_2.

Titanium and boron in combination are introduced into the melt by adding a pre-alloy type AlTiB (such as AlTi5B1, AlTi5B0.2), which contain effective elements Ti and B in form of intermetallic compounds TiB_2 and $TiAl_3$.
The intermetallic compound TiB_2 is insoluble in solid solution whereas AlB_2 and $TiAl_3$ are soluble in solid solution. This fact leads to some characteristic properties of softening the solid solution with one of the Ti or B elements individually.

Influence of vaccination on alloy properties

- increasing the strength and ductility,
- decreasing the tendency of the alloy to form fractures,
- lower porosity of casts,
- increase of cast tightness,
- better malleability,
- increase of properties after thermal processing.

3. Copper and its alloys

Time to study: 5 hours

Aim: After study of this chapter you will know

- Properties of copper, the influence of additives on Cu properties
- Basic classification of copper alloys
- Properties of copper alloys and their application

Lecture

properties of Cu

- high electrical and thermal conductivity
- good strength properties
- high melting point
- non-magnetic properties
- resistance against corrosion
- copper and its alloys are very attractive for transport of electrical energy, plumbing materials, casts and heat exchangers

The influence of additives on Cu properties

PHOSPHORUS

- strong de-oxidizing element, very intense (even at the content of 0.05% P - content of O_2 □ 0,001%)
- partially soluble in copper (300°C – 0,6; 400°C – 0,85; 500°C – 1,1; 600°C – 1,4; 714°C – 1,7)

- the content of phosphorus is de-oxidized copper – 0,02-0,05%
- at content of 0,05%, copper has the lowest strength and highest plasticity properties
- with the increasing amounts of P the strength properties increase slightly, but the electrical conductivity decreases significantly
- copper with 10-15% of P content is used for de-oxidation purposes.

NICKEL
- is completely soluble in liquid and solid state
- improves strength properties
- lowers electrical conductivity

ARSENIC
- reacts with copper to form Cu_3As (solubility in solid state copper of up to 8%)
- improves strength characteristics (minimally at normal temperature, more so at higher temperatures)
- steeply decreases electrical conductivity

ANTIMONY
- similar influence to arsenic

BISMUTH
- when in solid state, it is insoluble in copper
- released in eutectic morphology (eutect. t. 270,6°C)

LEAD
- when in solid state, it is insoluble in copper
- released in globulitic form - individual particles (eutect. t. 326°C)

IRON
- content of up to 0,2% does not influence mechanical properties significantly

Division of copper alloys

based on the main additive element, the Cu alloys can be divided into:
- brasses – alloys of copper and zinc (based on additive elements - manganese brass, nickel brass,...)
- bronzes – most alloys with other elements

Division of alloys based on the width of solidification range
- alloys with narrow interval of solidification up to approximately 50K: (yellow brasses, Mn,Al,Ni-bronze, CuZnNiSnPb, Cr copper)
- alloys with solidification interval of 50-110 K: (silicon brass, silicon bronze, Cu-Ni alloys)

- alloys with solidification interval of over 110 K (up to 170 K): (tin, leaded tin, red and lead bronze)

Influence of solidification interval on casting properties
- metal substitution
- macro- and micro- segregation

Bronzes

based on the main additive element or a group of additive elements, they are divided into these types of bronzes:
- tin
- leaded tin
- aluminum
- lead
- less – Cu-Ni, Cu-Cr, Cu-Mn, Cu-Si, Cu-Be

Tin bronzes
- alloying element– tin (9 – 13% Sn)
- nickel is released as an intermetallic alloy Ni3Sn
- increases strength properties
- nickel improves casting properties and resistance to corrosion

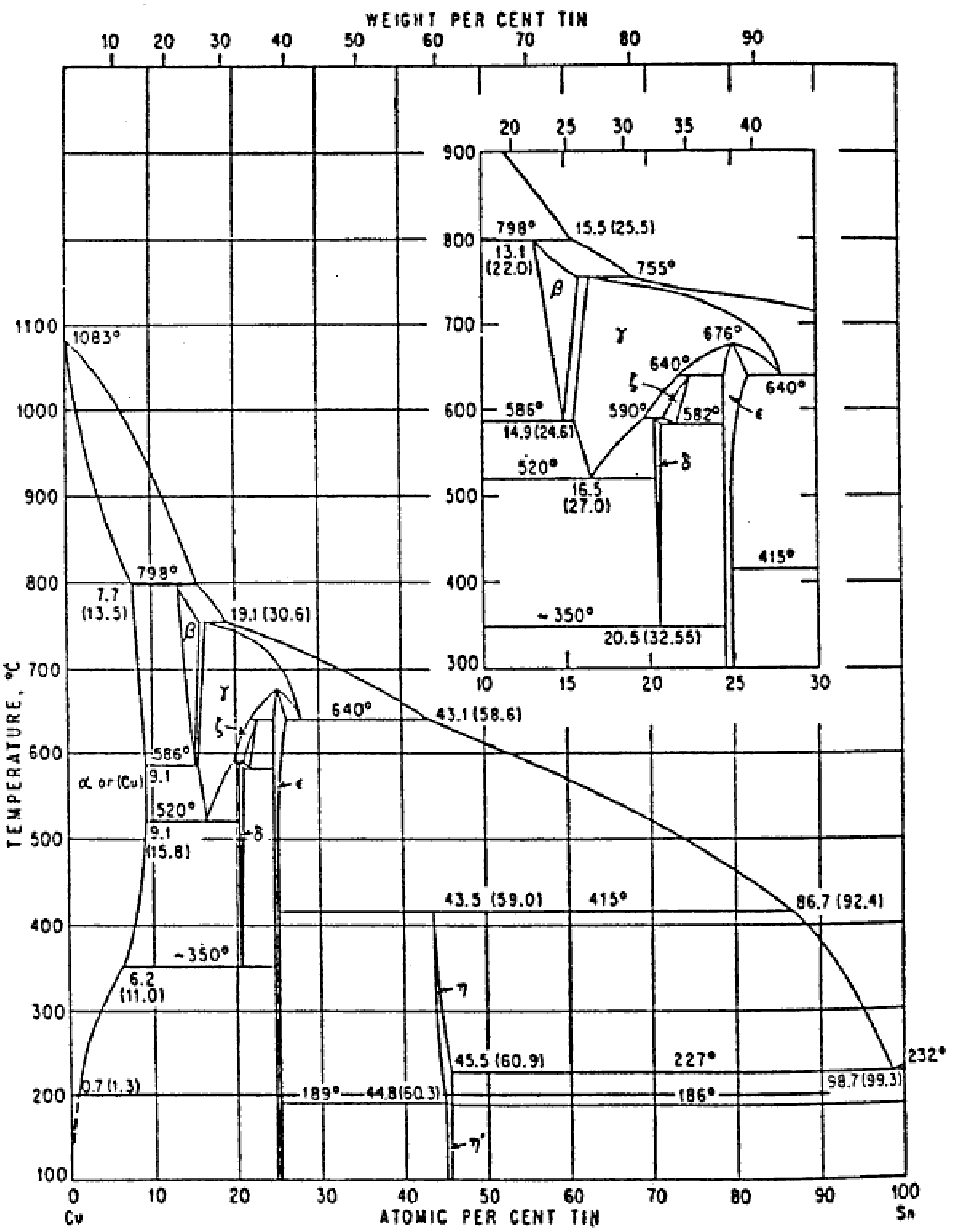
lead is in □ phase insoluble
- concentrates on the grain boundaries and in the areas of thermal axis
- improves malleability
- supports self-lubrication ability of bearings
- lowers strength and plasticity properties
- phosphorus
- bronze with 5-10% of Sn and up to 1% P – phosphorus bronze (as a bearing metal)

Diagram of Cu-Sn

α(Cu) – substitution solid solution of tin in copper

β and γ are high-temperature phases with relatively good plasticity properties (through fast cooling it is possible to stability β down to a normal temperature)

δ forms during cooling, at eutectoid transformation from β and γ phase (outstanding sliding properties)



Cu - Sn

nickel is released as an intermetallic alloy Ni3Sn

- increases strength properties
- nickel improves casting properties and corrosion resistance

lead is insoluble in its α phase

- it concentrates on the grain boundaries and in the thermal axis area
- improves malleability
- supports self-lubrication ability of bearings
- lowers strength and plasticity properties

use:
- casts in which good strength and high wear resistance is required
- casts worn by sliding friction, plain bearings, gears, pins, fittings, synchronizing rings

mechanical properties:
Rm 250-300 MPa
Rp0,5 140-170 MPa
A 10-30 %
HB 80-100

Special tin bronzes
- bell metal
  - 15 – 20 % of Sn
  - it is hard, has clear, metallic sound
- gunmetal (originally for cannon barrels)
  - 10 – 12 % of Sn
- spiegeleisen
  - 30 – 33 % of Sn
  - originally for production of optical mirrors or very accurate optical devices (it can be polished into high gloss)
- bronze for artistic casting
  - as a binary alloys with 7 - 12 % of Sn
  - also red bronze containing zinc

<u>Leaded tin bronze</u>
alloys of copper with tin, zinc and lead (red bronzes)
- 4 – 8 % Sn, 2 – 9 % Zn, 3 – 8 % Pb
- for example 5 % Sn, 5 % Zn, 5 % Pb

alloys of copper with tin and lead
- 8 - 11 % Sn, 8 - 23 % Pb, max. 2 % Zn

use:
red bronze is used as the cheapest variant of Sn-bronze (it has somewhat lower mechanical properties and especially strength - fittings casts, hydraulic components

mechanical properties:
- Rm 220-260 MPa
- Rp0,2 110-13 MPa
- A 15-20 %
- HB 60-70

use:
leaded tin bronze is used primarily for plain bearings for high loads, tight casts at high pressures, casts for steamy environments, corrosion resistant products,...

mechanical properties:

- Rm 180-220 MPa
- Rp0,2 90-110 MPa
- HB 50-70

<u>Aluminum bronze</u>

- depending on chemical composition– aluminum bronzes are binary or poly-component
- main alloying elements: Fe, Mn, Ni
- outstanding mechanical properties, high fatigue, wear, corrosion and cavitation resistance
- very narrow range between the liquid and solid temperatures (narrow two-phase range) dense structure and good tightness of the casts

structure:

- in cast state, it is composed by a mixture of α-phase and an eutectoid $(\alpha+\gamma_2)$, which was formed by the disintegration of high-temperature phase β
- in alloys with a content of nickel, phase γ_2 is substituted by poly-component phase κ, which contains Fe, Ni and Al

chemical composition of aluminum bronzes:

- 5 types of Al-bronzes – EN ČSN 1982
- 8 – 11 % of Al (max. 12 %)
- with increasing content of Al, the values of Rp0,2 and HB increase as well
- Fe (up to 3 %, uncommonly up to 6-7 %) softens the structure of the alloy and hardens the matrix through precipitations
- Mn (usually up to 2 %, max. 3 %) narrows the range of the α-phase and also increases strength
- Ni (1 – 6 %) increases mechanical properties (precipitation strengthening by the intermetallic phase CuFeNi, lowers the density

mechanical properties:

- outstandingly high mechanical properties
  - Rm 500 – 650 (750) MPa
  - Rp0,2 180 – 300 (380) MPa
  - A 15 – 30 (6)
  - HB 100 - 150 (180)
  - E 100 – 110 GPa
- thermal processing (alloys with over 10 % of Al content)
  - solution annealing (900°C-2 hours, α→β)

  - fast cooling → formation of unarranged β´- martensite
  - tempering at 560-620°C – 1 hour → precipitation of phase α and formation of tempered β martensite

fields of use:
- parts for pumps
- friction bearings for the highest loads
- gears, worm gears
- parts in non-sparking environment
- parts resistant to sea waters, saline solutions, brackish water and organic acids

Leaded bronze
- in liquid state, Pb and Cu are partially soluble, in solud state almost insoluble - the structure is made from crystals of almost pure copper and crystals of lead
- a big difference in density and solidification temperature - especially prone to segregation - frequent mixing of metal, special metallurgical interventions
- very good sliding properties - bearing metal
- contains up to 25 % of lead, 0 – 10 % of tin
- small amount of Ni, Sn, Zn or Mn softens the structure and limits lead segregation

Manganese bronze
- EN ČSN 1982 – 1 alloy
  - 8-15% Mn, 7-9%Al, 2-4% Fe, 1,5-4,5% Ni
  - material with high strength Rm over 630 MPa
  - ductility A > 18 %, high density
  - for production of weapons, turbines, bearings etc.
- alloys are homogenous with a content of up to 20 % of Mn, with fast cooling even alloys with higher content of Mn remain homogenous
- good mechanical properties (up to 300°C), good resistance to corrosion and specific electro-technical properties
- is not usually cast in foundries

Silicon bronze
- max. dissolvability of silicon in copper is 5,3 % Si
- > 5,3 % Si - formation of brittle phases limiting its technical use
- usually up to 3,5 % of Si
- alloyed by small amounts of Mn, Zn, Ni, Sn
- have good strength and high ductility up to 250°C
- suitable for use at low temperatures of – 180°C
- good chemical resistance in various chemical environments
- very good friction properties

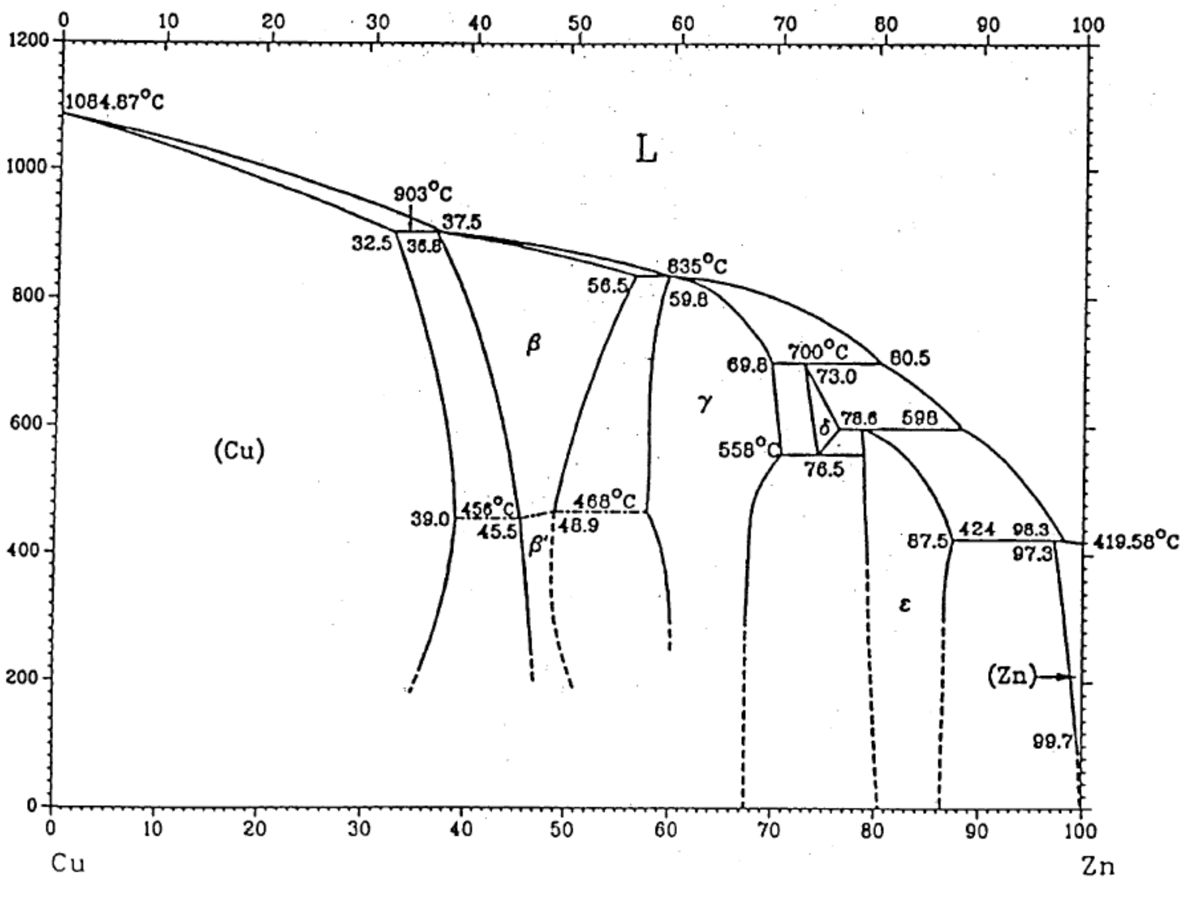
Nickel bronze (cupronickel)

- nickel has total solubility with copper in solid state □ any combination
- ↑ Ni ⇒ ↑ hardness and strength of alloys ↓ ductility
- good density, creep resistance and great corrosion resistance
- Cu-Ni-Zn (white cooper) with content of up to 20-25% of Ni, up to 10% of Zn, or containing Pb and Sn.
- ALPAKA – alloy with 55-65% of Cu, 18-27 % of Zn and approx. 18% Ni

Chrome copper

- used for casts that are required to have good resistance to abrasion and high electrical conductivity
- for example contacts for pantographs, electrodes for resistance welding, water-cooled lances of blast furnaces and cupola furnaces
- chrome forms alloy with copper with limited solubility and forms an eutectic
- eutectic concentration is 1,5% Cr, max. solubility of Cr in Cu at eutectic temperature is 0.65% Cr
- technical alloys contain 0.4-1.2% of Cr
- chemical composition is chosen with regards to achieving the required electrical conductivity

Brasses



- zinc forms substitution solid solution with copper □(Cu) with maximum solubility of 32,5% of Zn (at 903°C)
- with decreasing temperature, the solubility of zinc increases up to 39% (at temperature of 456°C)
- α phase has an FCC lattice and therefore good plasticity properties
- β phase has BCC (body centered cubic) lattice, appears in alloys with content of over 38% of Zinc
- β phase forms an unarranged solid solution based on electron compound CuZn and in thermal interval 468-456°C it transforms into a regularly arranged phase β´
- high-temperature phase β is dense and allows for hot forming
- phase β´ is brittle and causes decrease in density
- alloys formed only by phase β´ are practically technically useless (that's why the content of copper in brass is usually higher than approx. 55%)
- TOMBAK – alloys containing more than 80% of Cu
- casting brasses – contain a range of additives and impurities apart from Zn
  - „yellow brass“ – alloys based on elements CuZn(SnPb)
  - „white brass“ – contain high amounts of Mn (10 – 20%)
- brass solders
  - contain 42-54% of Zn and have melting temperatures of 840-880°C
  - silver solders for electro-technical purposes contain 30-50% of Cu, 25-52% of Zn, 4-45% of Ag

Influence of some important elements in brasses:

- iron – softens the grain, acts as crystallization nucleus (max. content of 0.5% of Fe), at amounts of over 0,35% it forms precipitates in the alloy
- nickel – dissolved in α-phase, increases density and corrosion resistance, usually amounts of up to 1% causes thickening of the grains
- manganese – is soluble in α-phase as well as β´ in contents of up to 4% of Mn (usual content is 0,2-0,5% of Mn, in alloyed brass as high as 5%)
- tin – very intensely narrows the area of α phase, increases fluidity of the melt, strength of the alloy, increases chemical resistance (especially to sea water), usual amounts are up to 0,5 – 1% of Sn
- lead – insoluble in α phase, decreases density, improved malleability, usually up to 1% of Pb, alloys with 3% of Pb – free cutting brasses
- silicon, selenium, tellurium, antimony and sulfur have negative effect on properties
- aluminum
  - in alloys for ingot casting
  - increases resistance to corrosion (formation of Al2O3 on the surface of the product), fitting casts and prevents solidification of moveable parts
  - usual amount is 0,15-0,3% of Al, in special brasses up to 3% (at casting into sand – content under 0,1%)

Brass structure:
influence of individual elements on the area of solid solution α is evaluated based on the so-called equivalent content of zinc.
equivalent coefficients of selected elements:
Si – 10, Al – 6, Mn – 0,5, Fe – 0,9, Ni – (-1,3), Pb – 1, Sn – 2, Mg – 2
for labeling in technical practice, the content of the basic element is used - i.e. copper (such as Ms 58 means that the alloy contains 58 % of Cu)

Properties of brasses:
- mechanical properties
- Rm– 200-300 MPa (manganese brass – Rm – 500-750)
- A – 10-20%
- HB – 70-100 (alloyed brasses up to 200)
    - depends on the value of zinc equivalent (34 – 45% Zn_{eqv})
    - the fraction of α phase decreases from 100 % to 0 %
    - strength in tension increases to approx. double the value, then it decreases rapidly
    - strength increases to double its value
    - ductility decreases to less then a half

casting properties:
- very narrow area of solidification - outstanding casting properties
- good fluidity and low tendency to formation of shrinkage porosity
- disadvantage – relatively significant linear shrinkage– approx. 1,5 %

usage
- production of plumbing fittings
- component of pumps, cases, machine parts
- components working in environment of saline solution

4. Magnesium and its alloys

Time to study: 5 hours

Aim: After study of this chapter you will know

- Properties of magnesium, the influence of additives on Mg properties
- Basic classification of magnesium alloys
- Properties of magnesium alloys and their application

Lecture

Magnesium and its alloys

- crystallizes in an HCP system - cannot be formed at normal temperature, deforms by twinning under mechanical load,
- pure magnesium and conventionally cast alloys of magnesium have a tendency to form brittle inter-crystalline fractures in planes of twinning or in basal planes {0001},
- at temperatures over 225 °C new basal planes are formed {1011} and magnesium stays well malleable material

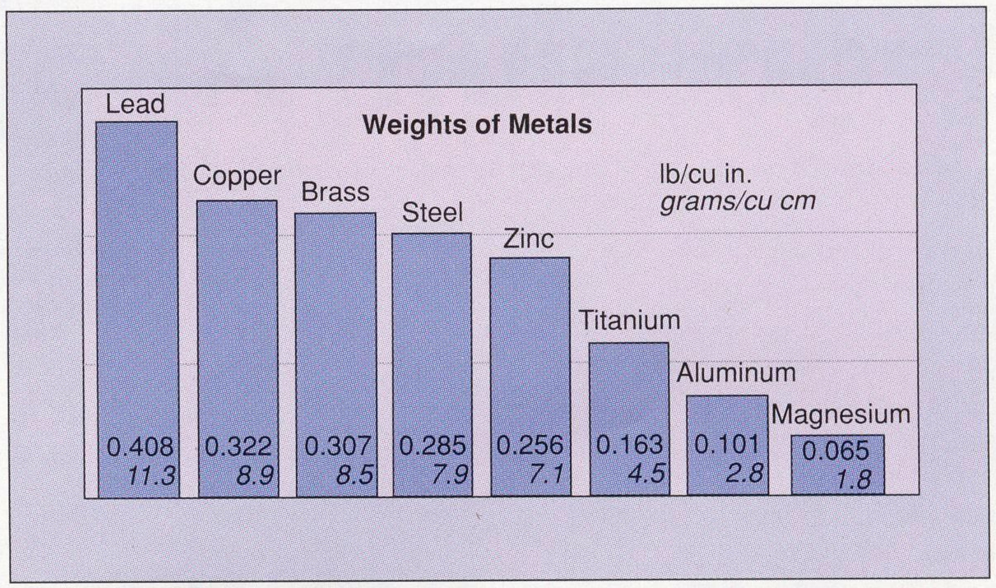


Fig. 1. Magnesium's light weight has allowed it to become the alloy of choice for a number of new markets and applications, such as the automotive, power tool, computer and electronics industries.

Casting alloys of magnesium

- main additive element– Al (Mg-Al)
- Mg-Li – super light alloys (1380 to 1480 kg . m-3)

labeling the Mg alloys:

- labeling system based on American ASTM norm
- (A – aluminum, C – copper, E – rare earth metals, M – manganese, S – silicon, Z – zinc)

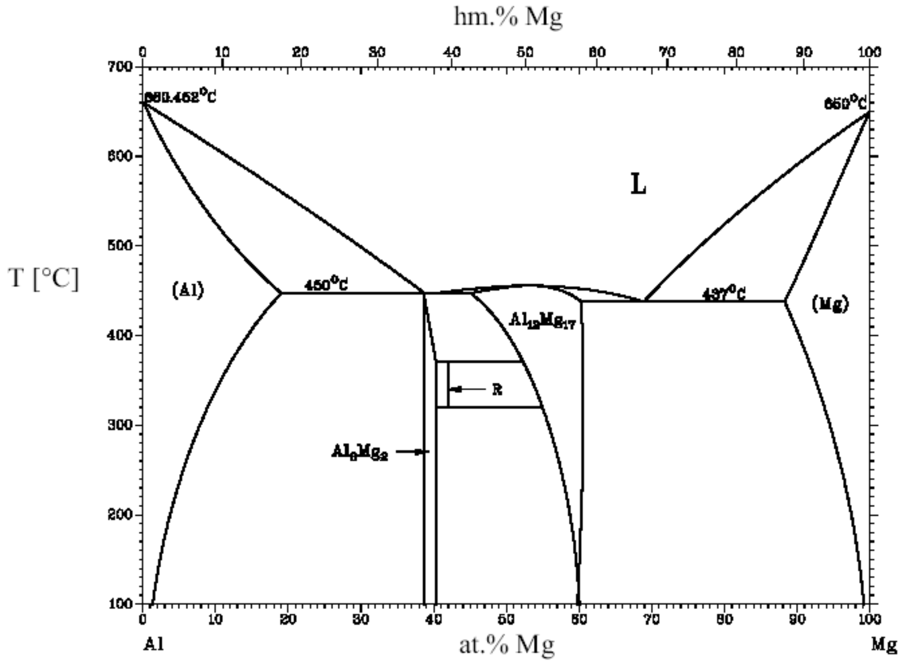


Diagram Mg – Al

- max. solubility of Al in Mg – 12,7 % at eutectic temperature 437°C
- at cooling from eutectic temperature, the solubility of Mg decreases - releasing intermetallic phase Mg17Al12 on the boundaries of dendritic grains - decreasing the malleability property of the alloy

Casting alloys of magnesium

- contain 3 to 9% of Al
- for gravitational casting, content of Al does not exceed 5 %
- with increasing content of Aluminum, fluidity is improved
- alloy for pressure casting– AZ 91
  - high strength, medium ductility and impact strength
- alloy with lower content of aluminum and zinc is replaced by manganese – AM20, AM50, AM60
  - higher ductility and strength (steering wheels in cars, seats)

- alloys containing 0,5-1 % of silicon - AS21, AS41
  - increase of mechanical properties
  - higher creep resistance
  - release of intermetallic phase Mg2Si (good stability at increased temperatures)
- alloys alloyed by rare earth metals
  - for applications at temperatures over 200°C
  - alloying elements – Ce, Nd, Th...
  - increased creep resistance
  - bad casting properties, gravitation casting into sand or metal molds

- AM 60 alloy for casting under high pressure with outstanding plasticity, used for rotors and car wheels

- AS 41 alloy for casting under pressure with good creep properties at up to 150°C; used for car parts
- AZ 81 alloys for casting into sand or ingots for general use in production
- AZ 91 airplane parts, engineering parts, gearbox housing
- AZ 91 alloy for casting under pressure for general use, for car and computer parts, chainsaws, sports equipment, cameras, projection devices, ...
- EZ 33 alloy for casting into sand and into ingots for use in high temperatures; outstanding casting properties; resistant to creep in temperatures up to 250°C and pressure-tight; used in aviation industry
- AZ 63 alloy for casting into ingots for so-called sacrificial anodes (anti-corrosion protection of boilers, tanks and pipelines)

Mechanical and physical properties of Mg alloys

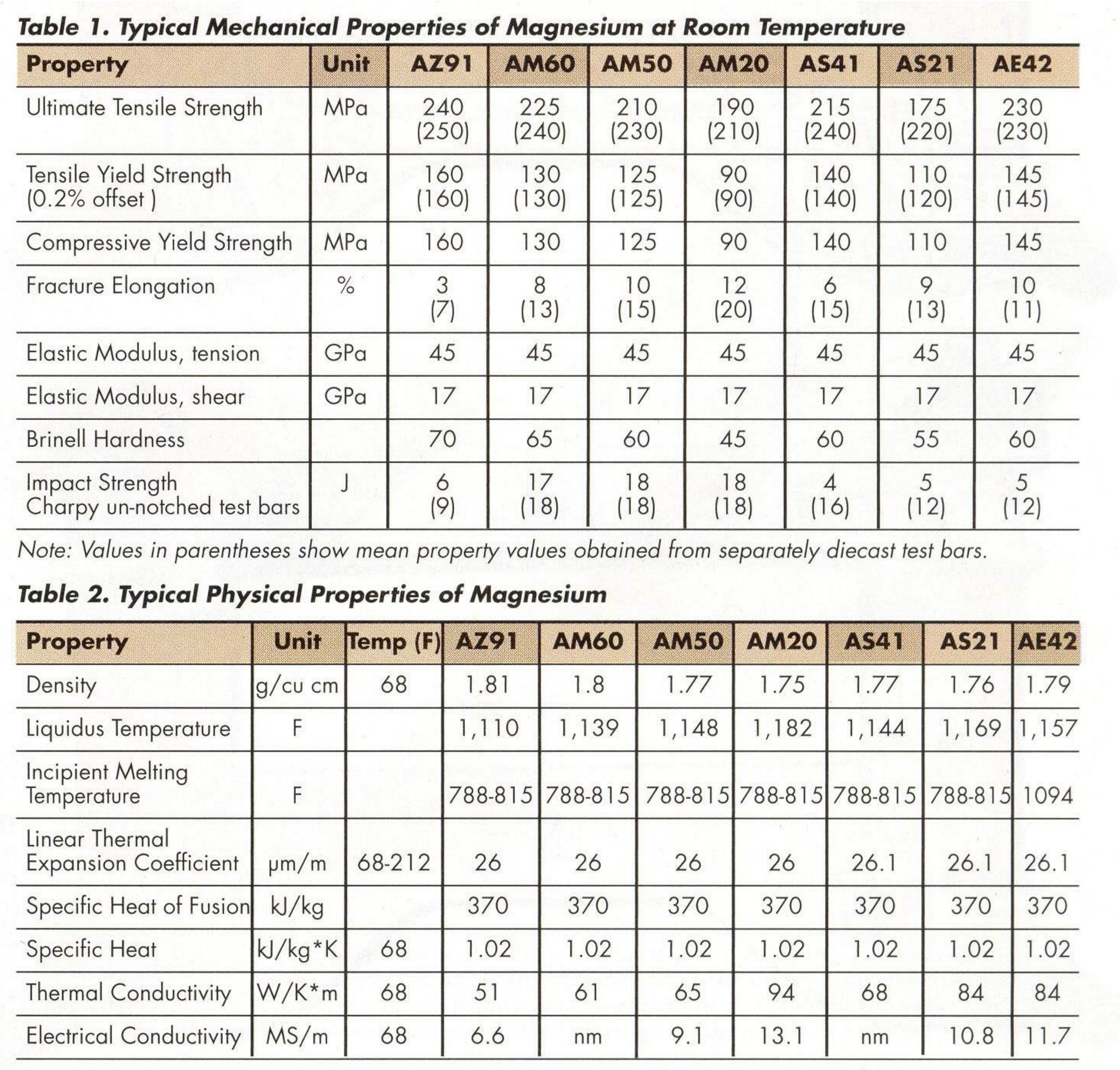


Table 1. Typical Mechanical Properties of Magnesium at Room Temperature

Property	Unit	AZ91	AM60	AM50	AM20	AS41	AS21	AE42
Ultimate Tensile Strength	MPa	240 (250)	225 (240)	210 (230)	190 (210)	215 (240)	175 (220)	230 (230)
Tensile Yield Strength (0.2% offset)	MPa	160 (160)	130 (130)	125 (125)	90 (90)	140 (140)	110 (120)	145 (145)
Compressive Yield Strength	MPa	160	130	125	90	140	110	145
Fracture Elongation	%	3 (7)	8 (13)	10 (15)	12 (20)	6 (15)	9 (13)	10 (11)
Elastic Modulus, tension	GPa	45	45	45	45	45	45	45
Elastic Modulus, shear	GPa	17	17	17	17	17	17	17
Brinell Hardness		70	65	60	45	60	55	60
Impact Strength Charpy un-notched test bars	J	6 (9)	17 (18)	18 (18)	18 (18)	4 (16)	5 (12)	5 (12)

Note: Values in parentheses show mean property values obtained from separately diecast test bars.

Table 2. Typical Physical Properties of Magnesium

Property	Unit	Temp (F)	AZ91	AM60	AM50	AM20	AS41	AS21	AE42
Density	g/cu cm	68	1.81	1.8	1.77	1.75	1.77	1.76	1.79
Liquidus Temperature	F		1,110	1,139	1,148	1,182	1,144	1,169	1,157
Incipient Melting Temperature	F		788-815	788-815	788-815	788-815	788-815	788-815	1094
Linear Thermal Expansion Coefficient	μm/m	68-212	26	26	26	26	26.1	26.1	26.1
Specific Heat of Fusion	kJ/kg		370	370	370	370	370	370	370
Specific Heat	kJ/kg*K	68	1.02	1.02	1.02	1.02	1.02	1.02	1.02
Thermal Conductivity	W/K*m	68	51	61	65	94	68	84	84
Electrical Conductivity	MS/m	68	6.6	nm	9.1	13.1	nm	10.8	11.7

This 2.3-lb AM60B magnesium shift tower assembly is a one-piece diecast component. Converted from a multiple steel fabrication, the magnesium casting design resulted in a 75% weight savings.

machine and is the "standard" of the cutting tool industry when comparing machinability of metals. The low power requirements for machining magnesium

as the easiest of structural metals to

Assn., Wheeling, Ill.

Design Considerations

When evaluating the various alloys and processes for a magnesium casting, there are a number of characteristics to consider to obtain a quality, low-cost component. This includes the end-use application, the post-casting operations and how casting magnesium will factor into tooling costs.

High Stiffness-to-Weight Ratio—This characteristic is important where resistance to deflection is desired in a lightweight component.

Improved Die Life—Unlike molten

Cast through the rubber plaster molding process in AZ91D magnesium alloy, this projector frame and interface offered the customer improved durability and rigidity, high heat tolerance and eliminated EMI plating requirements when compared to its previous plastic injection mold design.

Examples of Mg alloy casts

Melting of Mg alloys

- high affinity of magnesium to oxygen
  - melting under a layer of protective slag or in an intert atmosphere
  - oxidation – formation of oxide inclusions, which are not expelled from the melt
- pre-heated batch is added into the liquid metal
- melting in electric resistance or induction furnaces (resistance furnaces are more suitable)
- crucibles – carbon or low-alloyed steel
- furnace lining - based on magnesium oxides

- protection of metallic layer using
  - refinement salts (mixture of chlorides, event. fluorides, calcium, magnesium, sodium and potassium - refinement of the melt (bonding of inclusions))
  - sulfurs
  - inert gasses SO_2, SF_6, CO_2, Ar...

    0,2-0,3 % of SF_6

    $Mg + SF_6 + air \rightarrow MgO$ (protective coating)

5. Zinc and its alloys

Time to study: 1 hours

Aim: After study of this chapter you will know

- Properties of zinc, the influence of additives on Zn properties
- Basic classification of zinc alloys
- Properties of zinc alloys and their application

Lecture

Zinc

$\rho = 7130$ kg/m^3
$t_{melt} = 419°C$
$t_{boil} = 906°C$
crystallization within a hexagonal system

Casting alloys of zinc
- main alloying element – aluminum
- in a Zn-Al system, the primary phase has limited solubility
- an eutectic is formed by the Zn-ZnAl phase
- eutectic temperature is 381°C at the concentration of 5,5% of Al
- amount of aluminum in normed alloys (4-27%)

Secondary additive elements
- copper
  - decreases grain size (such as Al)
  - increases mechanical properties – strength, ductility, impact strength
  - improves fluidity of alloys
    - > 0,7 % Cu improves resistance to corrosion
  - usually approx. (0,5-3 % of Cu) in alloys

- magnesium
  - increases strength even in small amounts
  - compensates for damaging influence of tin, lead and cadmium
  - usually approx. 0,01 – 0,03 % Mg
  - ZAMAK

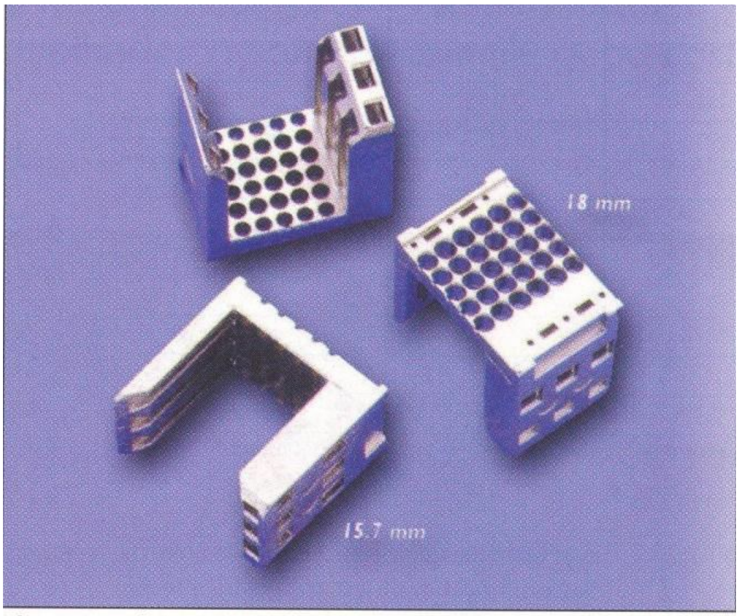
Impurities in Zn alloys
- primarily iron, lead, cadmium and tin
- support the formation of inter-crystalline corrosion
- content cannot exceed a thousandth of one percent - production must start from a very pure base metal containing 99,995 % of Zn

Chemical composition of alloys
- content of aluminum– 8, 12 and 27 % Al
- for pressure casting– 4% Al (Z400, Z410, Z430)

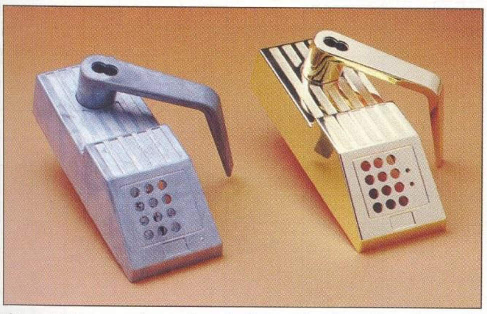
Casting properties
- very good casting properties (ZnAl8 and ZnAl11 – narrow area of solidification) - outstanding tightness
- casting temperatures: 455-610°C - high service life of metallic forms
- outstanding fluidity - thin-walled casts of complex shapes
- pressure casting
  - wall thickness up to 0,3 mm

  - pre-casting of openings with diameter up to 1 mm
- high precision of casts (from 0,03 mm)

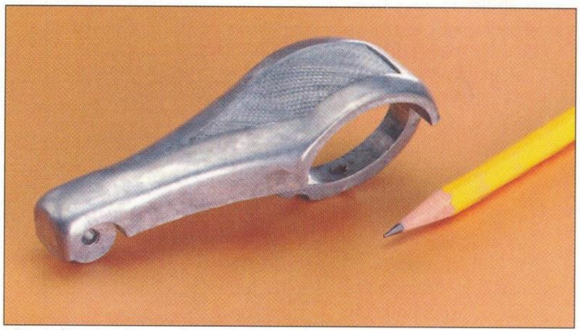
Examples of casts from zinc alloys



These Number 3 zinc alloy connector shields are as-cast for Berg Electronics.



This outside cover for a door lock for Mas-Hamilton Group is cast in zinc (l) and plated for a decorative finish (r).



Pictured is a miniature zinc casket arm. This component weighs less than 6 oz.

Examples of casts
- gas meter case
- bodies of heat exchangers
- for automotive industry (carburetor, headlight frames)
- smaller gears
- decorative objects

6. Titanium and its alloys

Time to study: 2 hours

Aim: After study of this chapter you will know

- Properties of titanium, the influence of additives on Ti properties
- Basic classification of titanium alloys
- Properties of titanium alloys and their application

Lecture

Properties of titanium

- Melting temperature: 1668 °C
- Boiling temperature: 3287 °C
- Specific mass: 4,51 g/cm^3
- grey or silver white. Abundant in the Earth's crust.
- Belongs to the group of metals difficult to melt.
- Up to 882°C - hexagonal lattice with close arrangement - stable α(Ti) modification.
- Over 882°C - BCC lattice - stable β(Ti) modification.
- Biocompatible

Dentures and hip replacements

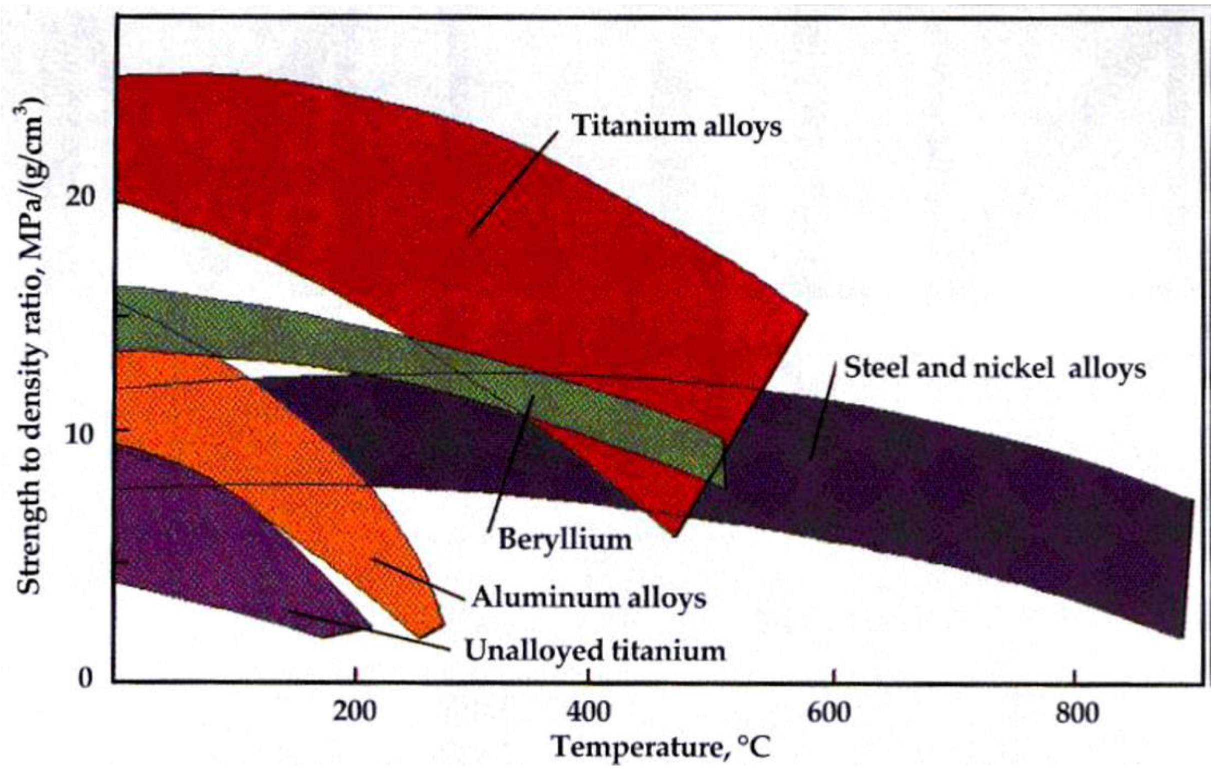
Titanium alloys

- Most commonly used titanium alloy is pure TiO_2.

- Used in production of dyes, in glass and ceramic industry, in production high-quality paper, as filler in production of plastics, sometimes added into toothpastes.
- Used in food industry in milk packaging.
- It is assumed that TiO_2 makes up over 90 % of the worldwide titanium consumption of titanium.

Titanium alloys

- The highest ratio between strength and specific mass
- Outstanding anti-corrosion properties
- Very good abrasion resistance
- Biocompatibility



Use of Ti alloys

- Use in aviation and aerospace industry
- In chemical industry, titanium is used in production or padding of chemical reactors.
- Material for production of wristwatches, glasses or jewelry parts.
- Apart from these applications, titanium can be found in art, such as coating on Mother Motherland, Kiev.

Division of titanium alloys

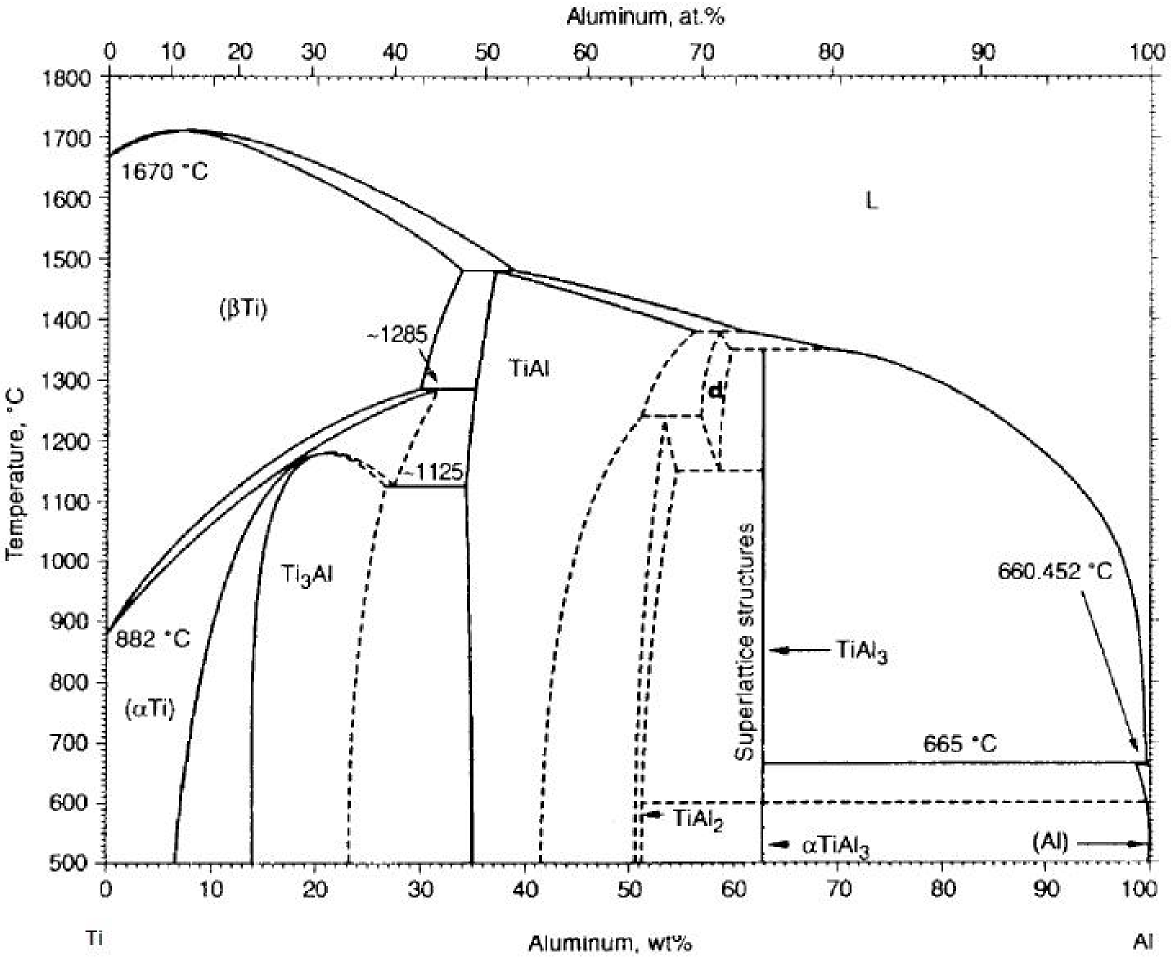
Ti alloys are divided based on their structure:

- α alloys

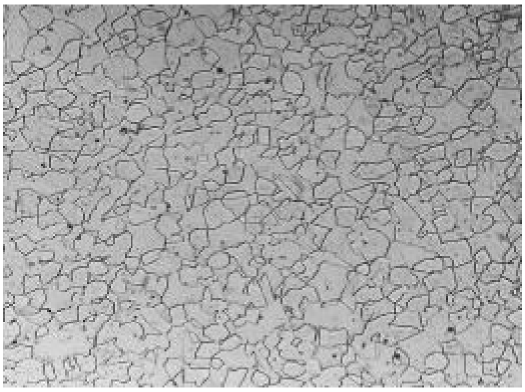
- pseudo α-alloys
- dual-phase alloys α + β
- pseudo β-alloys
- β-alloys
- intermetallic alloys

<u>α alloys</u>

- Main additive element is aluminum.
- TiAl5Sn2,5 is among the most common alloys.
- Structurally stable and usable in up to 500 - 550 °C.
- Good mechanical properties at low or very low temperatures (-200 °C) - cryogenic applications.
- Used in form of sheets for wings, tail areas, covering the engines and cabin, fuel tanks and reservoirs.



Binary diagram Ti – Al



microstructure of an α alloy TiAl5Sn2,5; 750x

α + β alloy

- Highest number of titanium alloys belong to this group.
- The most famous is TiAl6V4, which after TP can achieve strength of 1100MPa.
- Used for production of complex shape parts with resistance to vibrations (engine parts, compressor blades, etc.).
- Another alloy of this group is TiAl6Nb7, which is biocompatible and used in production of implants.

β alloys

- Elements V, Nb, Ta etc. stability high-temperature β modification even at room temperatures.
- TiV10Fe2Al3 alloy achieves strength up to 1400MPa.
- Used in aviation industry, for example in engines, springs and other applications.

Intermetallic alloys

- Because high degree of alloying, these alloys are formed by intermetallic phases.
- Ti – Ni alloys with shape memory consist of approx. 50% Ni and 50% Ti.
- Ti – Al has low specific mass and high stability of mechanical values even at high temperatures - for production of parts of aircraft jet engines.

Titanium foams

Use in medicine where they can lighten the implants and give them properties similar to human bones, such as impact softening.