Magnesium Alloys

- Magnesium is one of the lightest elements of density 1,78 g/cm
- It cerystallizes in a hexagonal lattice with c/a = 1.66
- Pure magnesium has a low mechanical properties with UTS =120 MPa
- Melting temperature 650^{o}C
- Large chemical attraction to oxygrn and nitrogen
- Produced in electrolytical way with content of impurities 0.05 and 0.1%
- Up to 2.8% is in solution in see water as dolomite (CaMg(CO3)2), magnesite (MgCO3) i carnalite (KMgCl3.6H2O).
- It can be found as solid ore in such countries as USA, England, Australia, Russia,Thailand

Application of magnesium

Zastosowanie	Udział, %
Konstrukcyjne, w tym: constructional	15
- odlewy matrycowe Die castings	11,3÷11,4
- odlewy grawitacyjne	0,8
- produkty walcowane Rolled products	2,9
Niekonstrukcyjne, w tym: nonconstructional	85
- dodatek stopowy w stopach Al Alloying addition Al. alloys	53,5
- odsiarczanie disulfiding	11,5
- modyfikacja żeliwa Cast iron modification spheroidization	6,3
- redukcja metali Reduction of other metals (Ti)	4,1
- chemikalia	3,2
- elektrochemikalia	3,2
- inne	3,2

Cam and mobile phone bodies.

Magnesium side panels

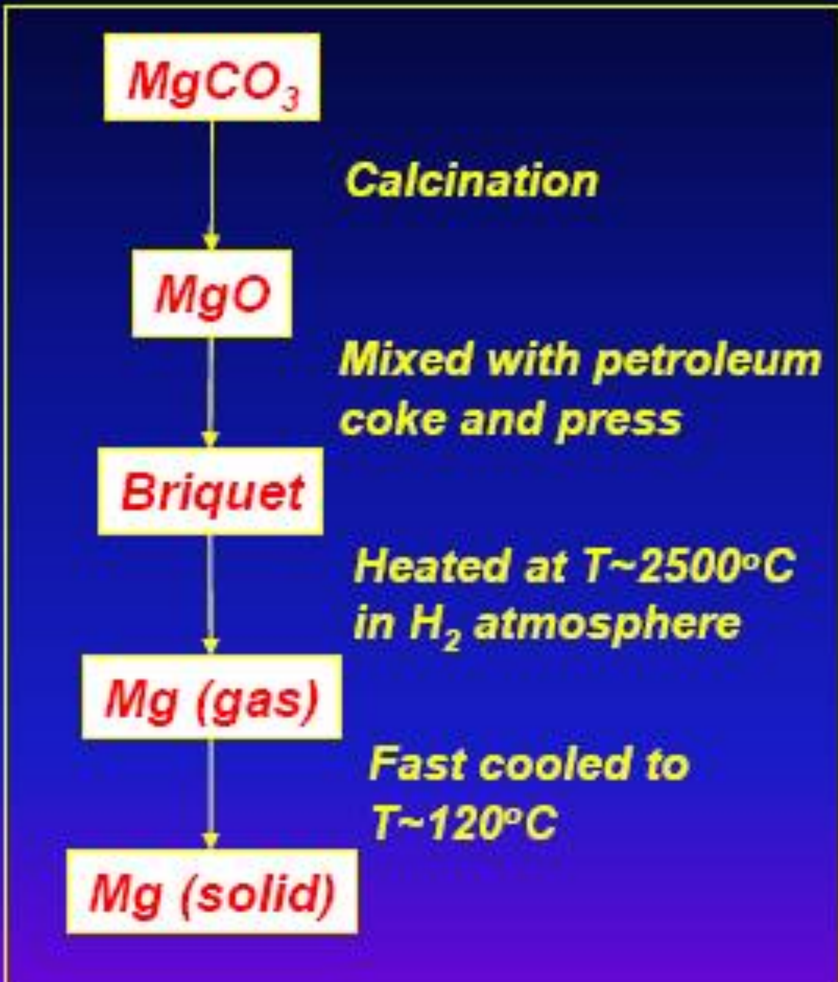
Alloyed wheel

Gearbox housing in the VW-Passat

Aerospace applications

Main application is for cast parts in automotive industry.

Calcination

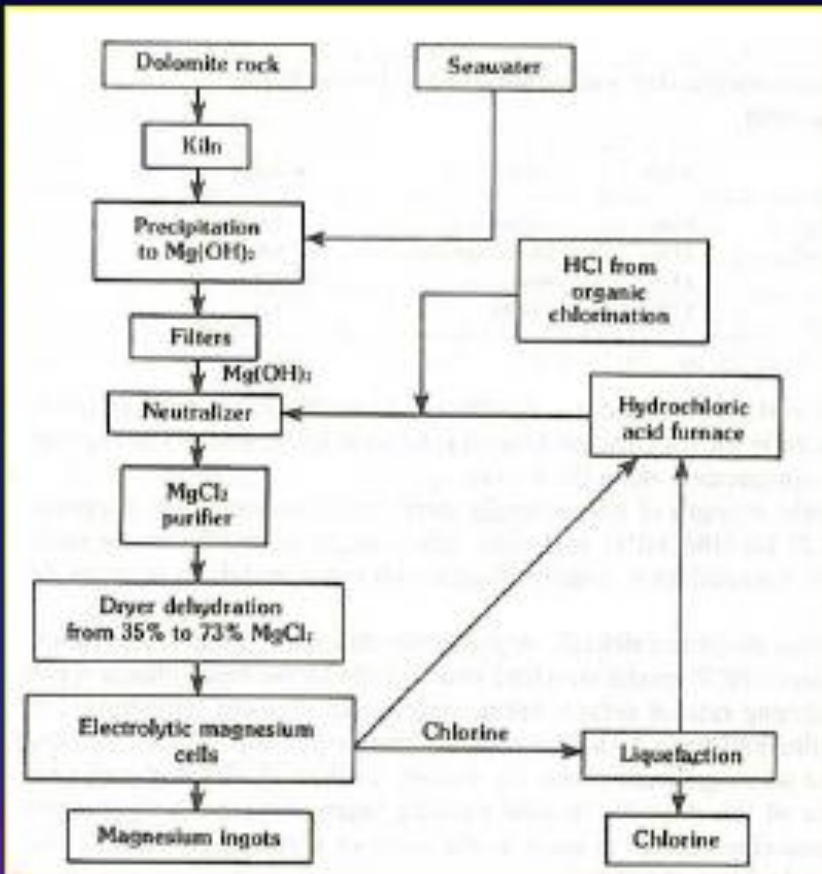


- ***$MgCO_3$*** is calcined to produce ***MgO***.
- ***MgO*** is then mixed with ***petroleum coke*** and pressed into solid block, called ***briquet***.
- Briquet is heated to ~2500°C to give ***Mg gas*** and cooled down to ~120°C to give ***Mg solid***.

$$MgO + coke \rightarrow Mg + CO$$

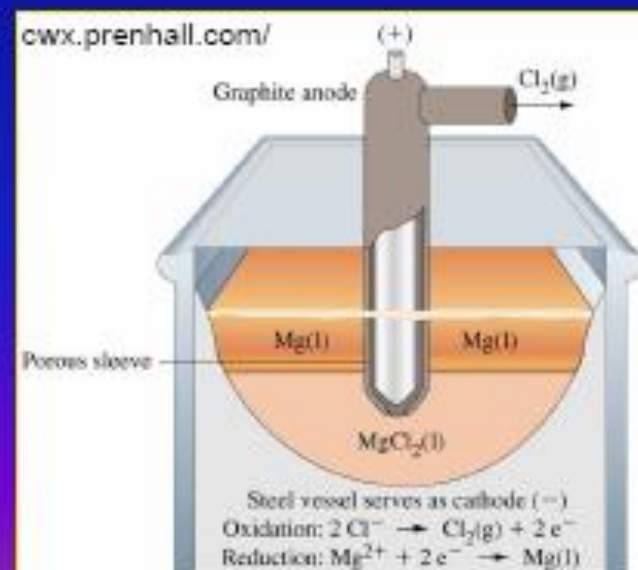
Note: *Boiling point of Mg ~ 1090°C*

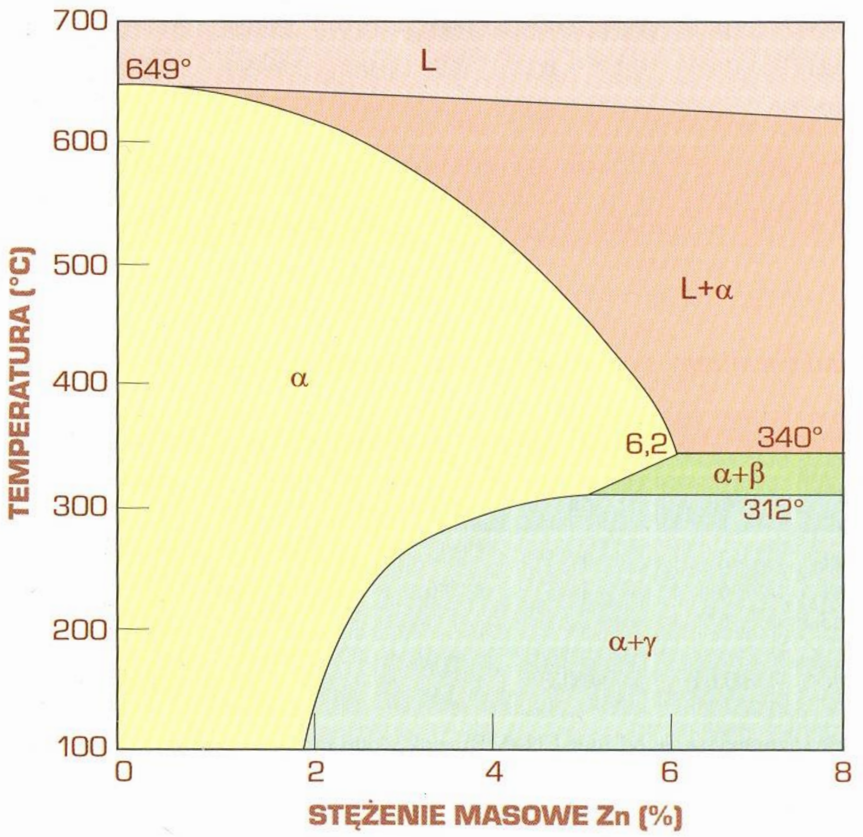
Electrolysis of magnesium



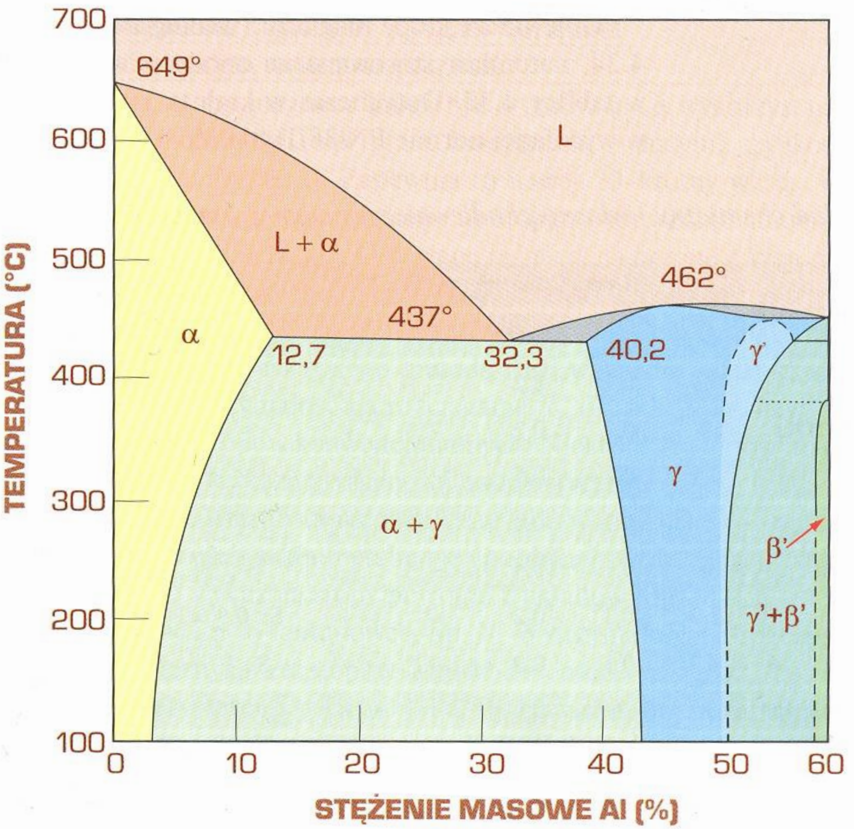
Electrochemical process for the extraction of magnesium

- Dolomite and seawater is precipitated as insoluble magnesium hydroxide ***$Mg(OH)_2$*** which is subsequently treated with ***HCl*** to give ***$MgCl_2$***.
- ***$MgCl_2$*** is fed into ***electrolysis cell*** to produce ***Mg*** metal at ***cathode*** and ***Cl_2*** at ***anode***.





Phase diagram Mg-Zn



Phase diagram Mg-Al

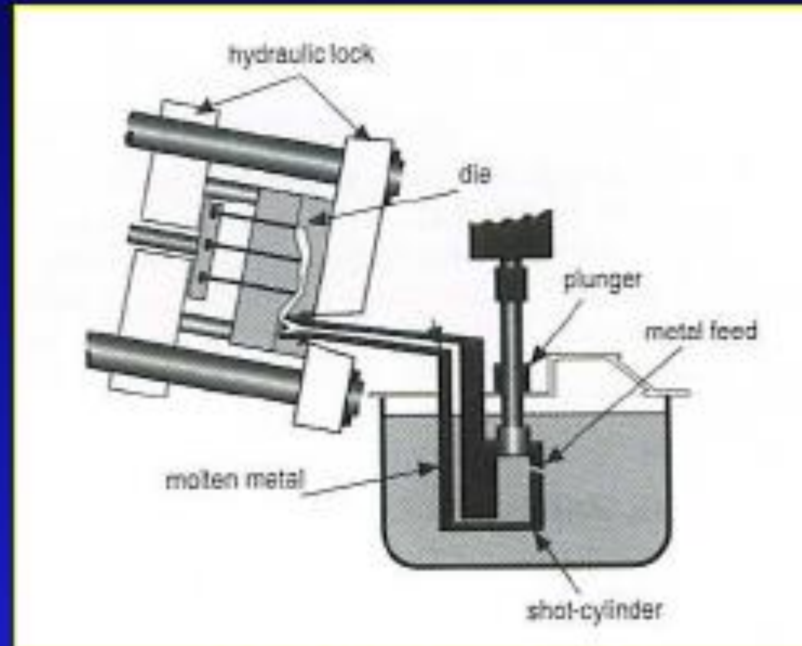
Hot-chamber die casting

- The hot chamber machine has a ***casting case*** with an integrated ***casting chamber*** that always stays within the ***casting furnace*** filled with molten metal.

- The molten metal is injected into the die by the downward motion of the plunger.

- Suitable for ***thin-walled parts***.

- ***High productivity*** (> 100 shots/hr) due to magnesium's excellent castability and rapid solidification.



Hot-chamber die casting

Capacity	Machine size ~ 900 ton Pressure of the melt ~150-120 bar Shot is limited to 5-6 kg Typical wall thickness 1 mm

Cold-chamber die casting

• The casting case is outside of the melt. The metal is pumped from a nearby furnace and put into the horizontal shot chamber.

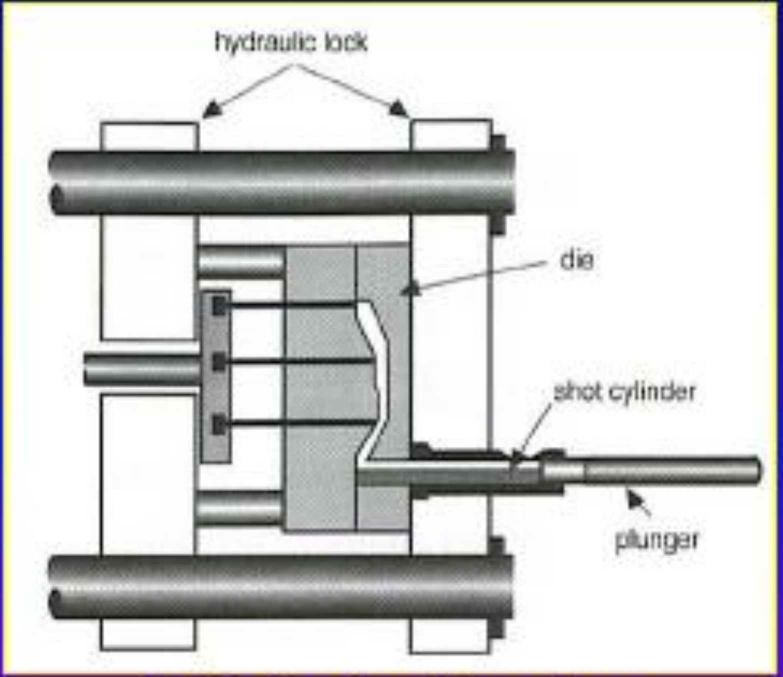
• The metal is then injected by the plunger into the die under high pressure.

• Used for ***large castings*** with ***heavy wall thickness***.

• ***Higher pressure*** is required to compensate high degree of shrinkage.

Capacity

Machine sizes upto 4,500 ton
Pressure of the melt ~300-900 bar
The shot is limited to 60 kg.
Wall thickness from 1.5-2.5 mm.



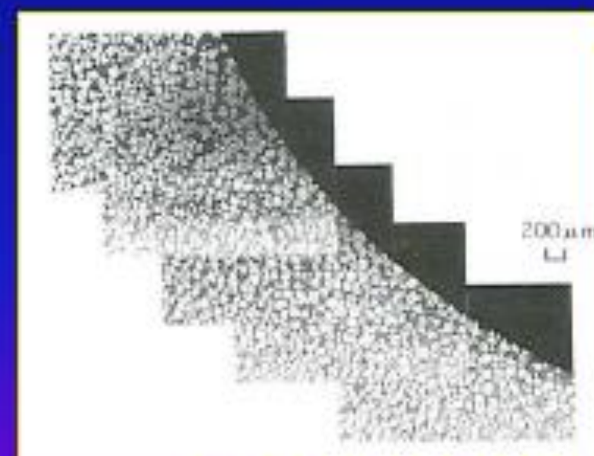
Cold-chamber die casting

Advantages of thixo-casting

Thin-walled Mg alloy AZ91D casting produced by thixo-moulding

Advantages:

- Production can be fully automated.
- High productivity
- Cost saving due to low energy consumption
- Higher tool lifecycles
- Gas-inclusion-free parts → weldable
- Low cooling shrinkage and no blow holes
- Parts have excellent mechanical properties (fine grained)
- Produce thin-walled casting parts
- Near-net shape quality



Crack-free surface of a thixo-cast component (AZ91D)

Mg-Al-Zn casting alloys

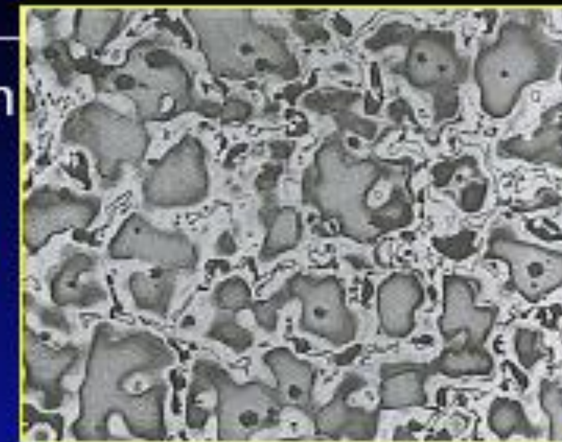
- Light weight, strength and relatively good corrosion resistance and easily cast.
- ***Zn addition*** increases strength by ***solid solution strengthening*** and ***precipitation hardening***.
- σ_{TS} ~ 214-241 MPa with 1-8% elongation.

- A network of $Mg_{17}Al_{12}$ or β phase is formed around GBs in the as-cast condition, *fig (a)*. → reduce σ_{TS}, *%E*.
- More slowly cooled alloy appears discontinuous β phase at GBs with a cellular or ***pearlitic structure***, *fig (b)*.

↓

T6 temper | $Mg_{17}Al_{12}$ is refined and uniformly distributed. → improved properties.

Note: AZ91 is the most widely used (die cast) due to fine and uniform as-cast structure.



(a) Chill cast alloy with the β phase ($Mg_{17}Al_{12}$) at grain boundaries.

(b) Discontinuous precipitation in more slowly cooled alloy.

Cast structures of AZ80 alloy

Mg-Zn-Zr and Mg-RE-Zn-Zr casting alloys

Mg-Zn-Zr alloys

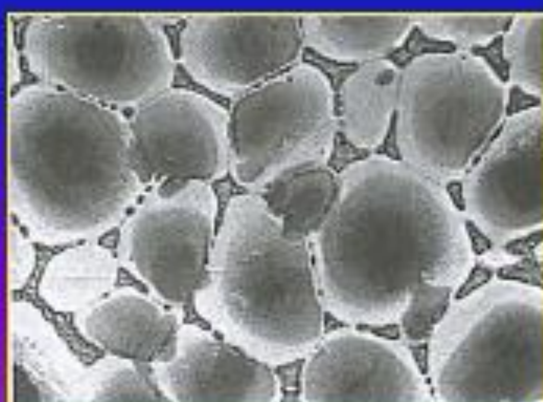
- **ZK51** and **ZK61** are sand cast
5-6% ***Zn*** addition → ***SS*** strengthening
1% ***Zr*** addition → grain refinement.

- The alloys have ***limited use*** due to their susceptibility to ***microporosity*** during casting and ***not weldable*** due to ***high Zn content***.

Mg-RE-Zn-Zr alloys

- ***RE (Ce, Nd)*** is added to produce **EZ33** and **ZE41** (sand cast), giving ***good castability*** due to ***low-melting point eutectics*** formed as networks in ***GBs*** during solidification. → microporosity ↓ .

- Lower strength due to removal of ***Zn*** from ***SS*** to form the stable ***Mg-Zn-RE phase*** in ***GBs***.



Mg-RE-Zn-Zr alloy as cast and heated at 400°C 48 h

Precipitation sequence

$$Mg_{ssss} \rightarrow GP\ zones \rightarrow \beta'' \rightarrow \beta' \rightarrow \beta(Mg_{12}Nd)$$

Note: *β'' phase is the main strengthening precipitates*

High-temperature magnesium casting alloys

- *Primarily used for aerospace applications due to light weight (major consideration).*
- *Application range 200-250°C with tensile strength ~240 MPa.*

- ***Mg-Ag-RE alloys***

QE22 has been used for aerospace applications, i.e., landing wheels, gear box housings.

- ***Mg-Y-RE alloys***

WE43 has been developed for improved elevated temperature tensile properties.

- ***Mg-Ag-Th-RE-Zr alloys***

Thorium is best known to improve high temperature properties, due to age hardening and refined grain but slightly radioactive → not commercially available.

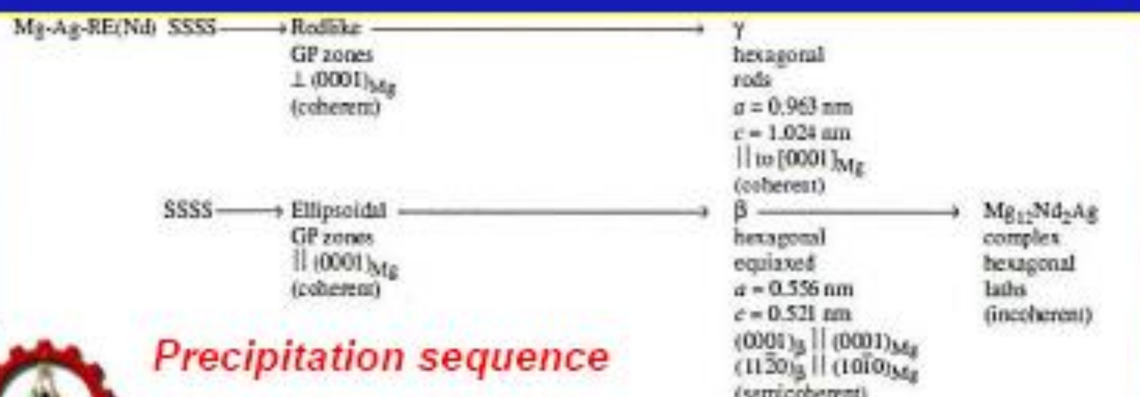
Mg-Ag-RE alloys

• ***Ag*** was found to have a positive effect on precipitation behaviour of ***Mg-RE*** alloys. → development of ***QE series*** to improve ***elevated temperature strength*** and ***creep resistance***.

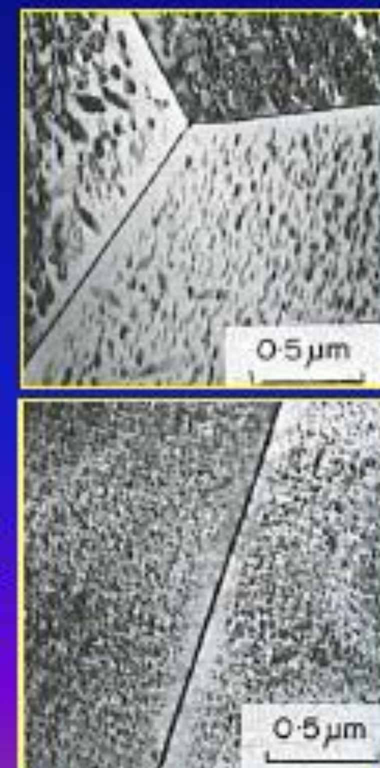
• ***Mg_9R*** compound is produced at ***GBs*** of ***Mg*** solids solution embedded with a fine precipitate of ***$Mg_{12}Nd_2Ag$*** precipitates.

QE22 (2.5% ***Ag*** and 2% ***RE*** such as ***Nd***) and other heavy ***RE*** gives

- Outstanding age-hardening response.
- Good tensile properties up to 200ºC.



Precipitation sequence



Ag addition ↓

Finer and higher V_f of precipitates

Mg-Y-RE alloys

Advantages:

- *Mg-Y alloys* are capable of age-hardening with solid solubility of ***Y*** up to 12.5 wt%.
- Good strength and creep resistance upto 300ºC.

Drawbacks:

- ***Y*** is expensive
- Difficult to alloy due to high T_m ~ 1500ºC.
- High affinity for oxygen.

WE43 (4% Y, 2.25% Nd, 1% heavy rare earths, 0.3% Zr)

- Improved high temperature properties.
- Maintained RT tensile strength of 250 MPa after long-term exposure at 200ºC.
- For advanced aerospace applications.

Mg-Y containing alloy

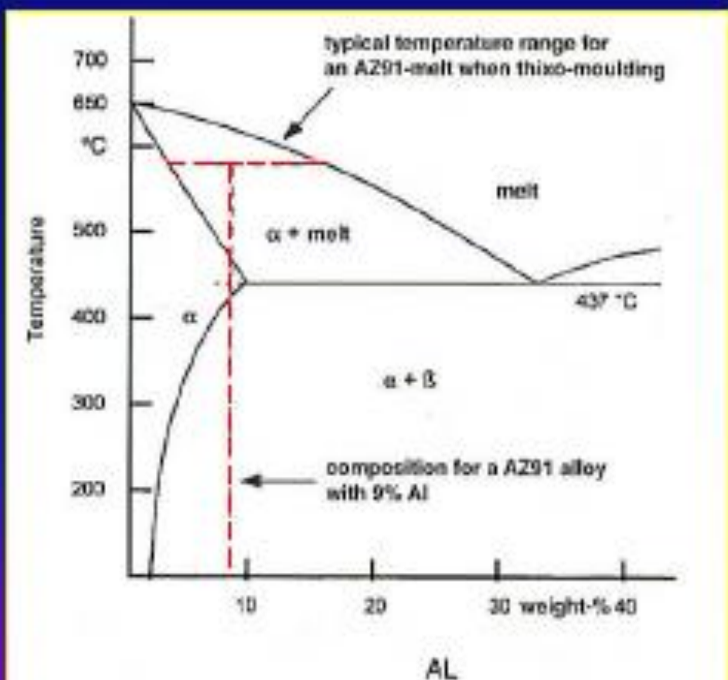
Thixo-casting

- Relatively new method based on ***thixotropic properties*** of semi-liquid alloys.

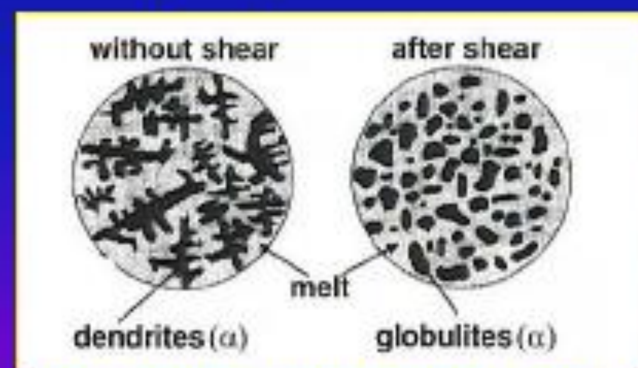
- Typical ***temperature range*** for ***thixo-casting*** is ~20ºC below the ***liquidus temperature*** and contains a mixture of solid and liquid phases → ***semi-solid metal forming***.

- Intense stirring changes ***dendrite*** → ***globular*** structure formation.

Viscosity ↑ ***Shearing strain*** ↓

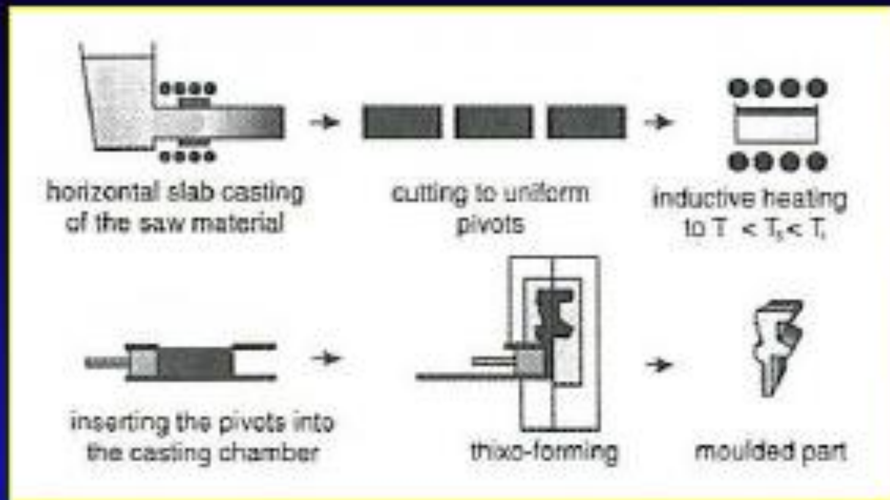


Mg/Al phase diagram for the thixo-casting/moulding process



Dendrite and globular formation of an Mg/Al alloy

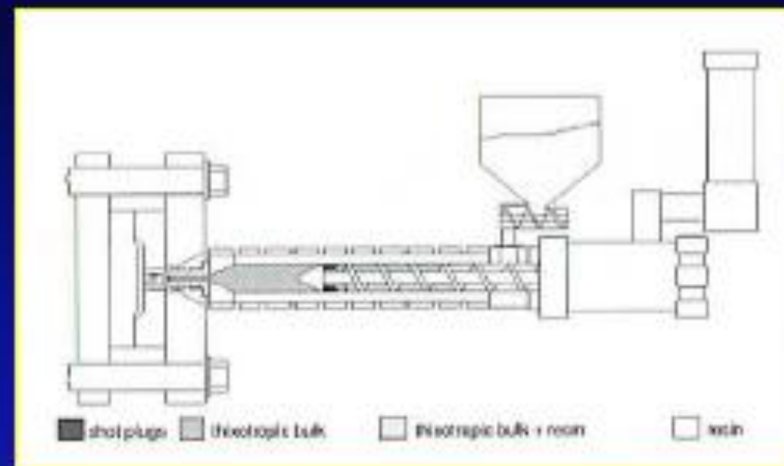
Sequence of thixo-casting process



- The slab is cut to provide uniform pivots, which are then heated up close to the $T_{liquidus}$ until the ***ratio of liq/sol*** (~30-40% melt) is reached.
- This heated metal lump is then transferred to the ***thixo-forming machine***.
- The pressure is applied to develop ***shearing stress***, which decreases viscosity and the metal lump now behaves like a ***fluid***.
- ***Electromagnatic stirring*** might be applied for a short period of time to avoid ***dendritic growth***.

Thixo-moulding

- ***Thixo-moulding*** is a variation of thixo-casting but using an ***injection moulding machine*** instead of the die-casting machine. (similar to plastic moulding).



Thixo-moulding casting machine prior to the shot

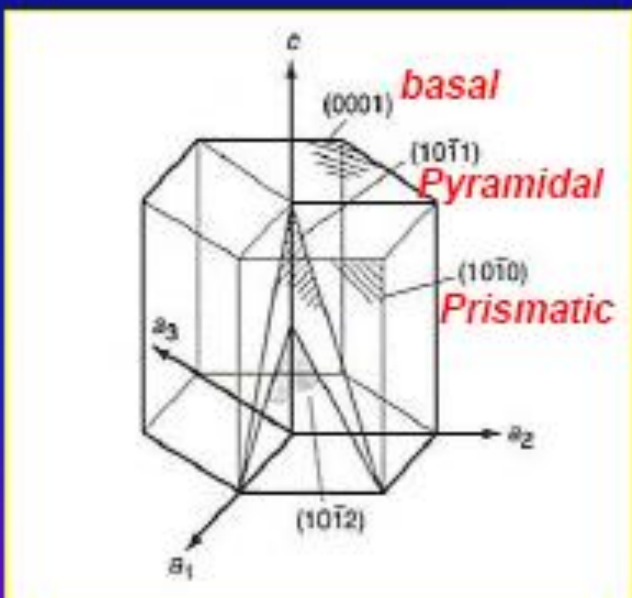
- The process involves ***melting the thixo-moulding granulate*** in a ***screw conveyer***, which leads to the ***chamber***. (***T*** ~ 560-620°C)
- The semi-solid melt is then pressed into the mould.
- The ***injection unit*** is protected with ***Ar*** during heating and cooling to ***prevent contact with air***.

Magnesium wrought alloys

Stop	**% Al**	**%Zn**	**%Mn**	**%Th**	**%Zr** lub Ca	**R_m MPa**	**A_5 [%]**
AZ10A	1-1.5	0.2-0.6	0.2	-	-	240	10
AZ21	1.6-2.5	0.8-1.6	0.15	-	-		
AZ31	2.5-3.5	0.6-1.4	0.2	-	-	290	15
AZ61	5.8-7.2	0.4-1.5	0.15	-	-	305	16
AZ80	7.8-8.2	0.2-0.8	0.12	-	-	338	11
HK31	-	0.3	-	2.5-4	0.4-1Z	260	23
HM21	-	-	0.45-1.1	1.5-2.5	-	235	
M1A	-	-	1.2	-	0.3 Ca	230	17

Wrought magnesium alloys

- Deformation is limited due to ***HCP structure***, only occur on
  1) By slip on the **{1000}** ***basal*** planes in the **$\langle 11\bar{2}0 \rangle$** direction.
  2) Twining on the **$\{10\bar{1}2\}$** ***pyramidal*** planes.
- At ***T>250°C*** slip can occurs on ***pyramidal*** and ***prismatic*** planes.



- More workable at elevated temperatures (300-500°C) rather than at ***RT***.
- ***Magnesium alloys*** are normally produced in ***sheets, plates, extruded bars, shapes , tubes, and forgings.***

Wrought magnesium alloy products

Extruded parts

Profiles of variable cross-section

A profile of large cross-section (6m long)

Anterior bars of vehicle

Extruded parts

Forged parts

Magnesium strips

Magnesium sheet (1500×1.8mm)

Sheet, strips

Forging of magnesium alloys

Advantages of forged magnesium components compared to commonly used die cast magnesium parts:

1) Excellent strength, especially with the fibres lying parallel to the main load direction.
2) Very good properties for pressure-sealed components because of a forging process in preventing a porous microstructure.

- *Grain size and multiphase microstructure are the main problems in magnesium forging. This can be overcome by additional extrusion process to give a sufficient grain size for forging.*
- *Complex component geometries are usually produced in several forging steps.*

Drop-forged gearbox cover for a helicopter

Forging of magnesium alloys

	forged magnesium wheel alloy: MgZn3Zr (ZK30)	forged aluminium wheel alloy: AlMgSi1 (AA6082-T6)
wheel weight	6,8 kg	10,5 kg
hardness	66,6 HRB	78 HRB
testing moment	3.000 Nm	3.000 Nm
load cycles	84.000	1.064.000

Prototype of a magnesium forged wheel(ZK30)

Produced on the basis of the corresponding aluminium part in series production for the Audi A8

Table 5: Strength properties of the magnesium wheel (ZK30)

Extraction point of the specimen	Orientation	Yield strength R_p 0.2 [MPa]	Tensile strength R_m [MPa]	Elongation at fracture, A [%]
rim	axial	248	302	13,7
	tangential	196	266	12,3
spoke/dish	axial	157	260	14,9
	tangential	203	265	12,3