

Production Technology 2 – Casting Technology

Winter semester 2024/2025

Rev.16, 19.11.2024



Lehrstuhl für Gießereitechnik
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Welcome to the *casting technology* lecture module!

Lecture schedule for the winter semester 24/25

Lecture	Chair	Date	Time	Room	
LU 1	REP	15 October 2024	Tuesday 16:15 - 17:45	H18	
LU 2	REP	22 October 2024	Tuesday 16:15 - 17:45	H18	
LU 3	REP	29 October 2024	Tuesday 16:15 - 17:45	H18	
LU 4	REP	05 November 2024	Tuesday 16:15 - 17:45	H18	
LU 5	LGT	12 November 2024	Tuesday 16:15 - 17:45	H18	Casting technology
LU 6	LGT	19 November 2024	Tuesday 16:15 - 17:45	H18	Casting technology
LU 7	LGT	26 November 2024	Tuesday 16:15 - 17:45	H18	Casting technology
LU 8	LGT	03 December 2024	Tuesday 16:15 - 17:45	H18	Casting technology
LU 9	FAPS	10 December 2024	Tuesday 16:15 - 17:45	H18	
LU 10	FAPS	17 December 2024	Tuesday 16:15 - 17:45	H18	
		24 December 2024			
		31 December 2024			
LU 11	FAPS	07 January 2025	Tuesday 16:15 - 17:45	H18	
LU 12	FAPS	14 January 2024	Tuesday 16:15 - 17:45	H18	

Welcome to the *casting technology* lecture module!

Exercise schedule for the winter semester 24/25

Exercice	Chair	Date	Time	Room	
		16 October 2024			
EX 1	REP	23 October 2024	Wednesday 14:15 - 15:45	H19	
EX 2	REP	30 October 2024	Wednesday 14:15 - 15:45	H19	
EX 3	REP	06 November 2024	Wednesday 14:15 - 15:45	H19	
EX 4	REP	13 November 2024	Wednesday 14:15 - 15:45	H19	
EX 5	LGT	20 November 2024	Wednesday 14:15 - 15:45	H19	Casting technology
EX 6	LGT	27 November 2024	Wednesday 14:15 - 15:45	H19	Casting technology
EX 7	LGT	04 December 2024	Wednesday 14:15 - 15:45	H19	Casting technology
EX 8	LGT	11 December 2024	Wednesday 14:15 - 15:45	H19	Casting technology
EX 9	FAPS	18 December 2024	Wednesday 14:15 - 15:45	H19	
		25 December 2024			
		01 January 2025			
EX 10	FAPS	08 January 2025	Wednesday 14:15 - 15:45	H19	
EX 11	FAPS	15 January 2024	Wednesday 14:15 - 15:45	H19	
EX 12	FAPS	22 January 2024	Wednesday 14:15 - 15:45	H19	

Sources | Recommended reading for the lecture

The contents of the lectures and exercises are based on the works mentioned here, unless otherwise stated. In particular, the researchers developed basic knowledge of material behavior in the context of different manufacturing processes.

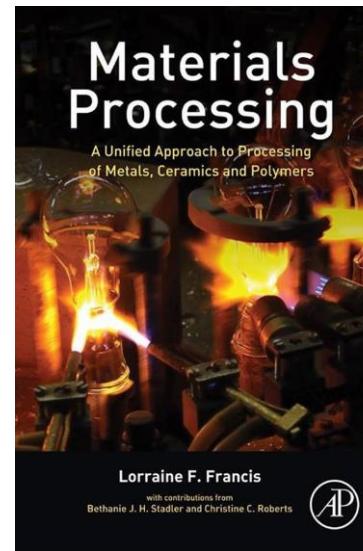


[SIN16]

Bernhard Ilschner, 1928 – 2006
Robert Friedrich Singer, 1950 – 2019

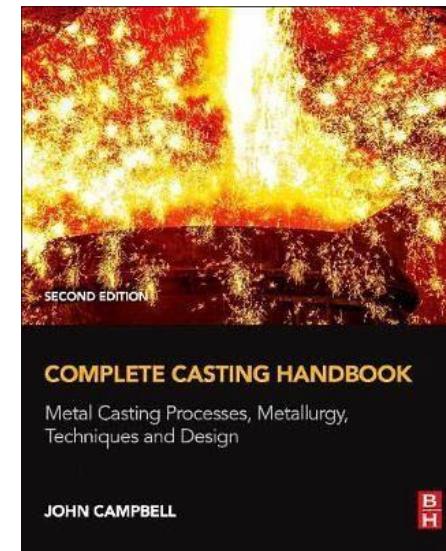
Bernhard Ilschner: Professor of Materials Science at FAU since 1965, also serving as founding director of the Institut für Werkstoffwissenschaften

Robert Friedrich Singer: Professor of Materials Science and Technology of Metals at FAU since 1991



[LOR16]

Lorraine F. Francis
College of Science and Engineering
Distinguished Professor, University of Minnesota



[CAM15]

John Campbell OBE
Appointed to the chair of casting technology at University of Birmingham, University Professor Emeritus

Further sources:

[DYE13] Dr. David Dye (2013): Microstructure and Properties of Materials, Phase Metallurgy, Lecture notes MSE 104, Imperial College London, Department of Materials

Andreas Höfler,
<https://www.tec-science.com>

Outline of the *casting technology* lecture module

Chapter	Title	Date
1	Introduction Physical fundamentals of casting technology	12.11.2024, 19.11.2024
2	Casting processes	19.11.2024, 26.11.2024
3	Materials: castability, alloys, heat treatment of cast components	26.11.2024, 03.12.2024
4	Designing a successful casting process	03.12.2024

Chapter	Introduction Physical fundamentals of casting technology	Date
1.1	Introduction	
1.2	Crystallization	
1.3	Speed of transformations	
1.4	Solidification morphologies of metals	
1.5	Melt rheology	

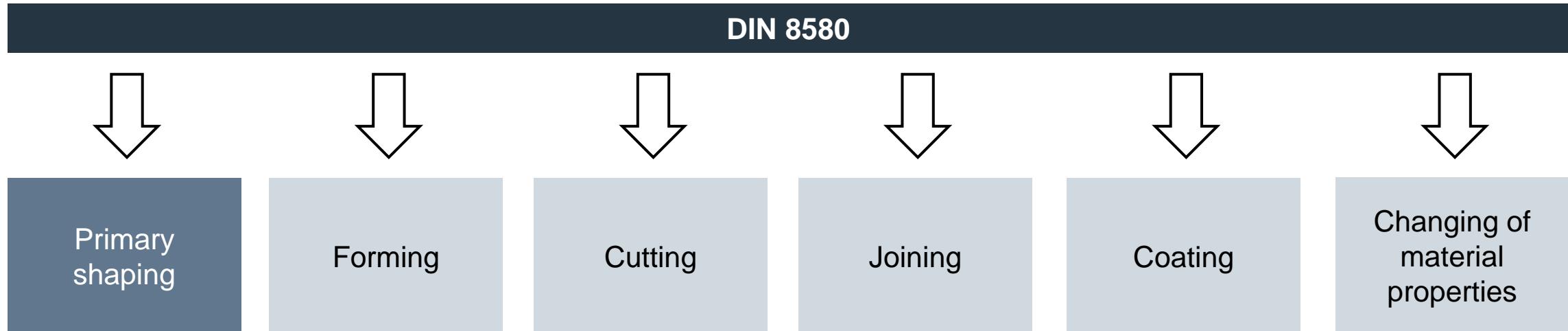
Outline Chapter 2 – 4

Chapter	Casting processes	Date
2.1	Sand casting	
2.2	Investment casting	
2.3	Permanent mold casting	
2.4	High pressure die casting	

Chapter	Materials: castability, alloys, heat treatment of cast components	Date
3.1	Definition of a castable alloy	
3.2	Shrinkage during solidification	
3.3	Ferrous alloys	
3.4	Non-Ferrous alloys	
3.5	Heat treatment of Al-alloys	

Chapter	Designing a successful casting process	Date
4	(No subchapter)	

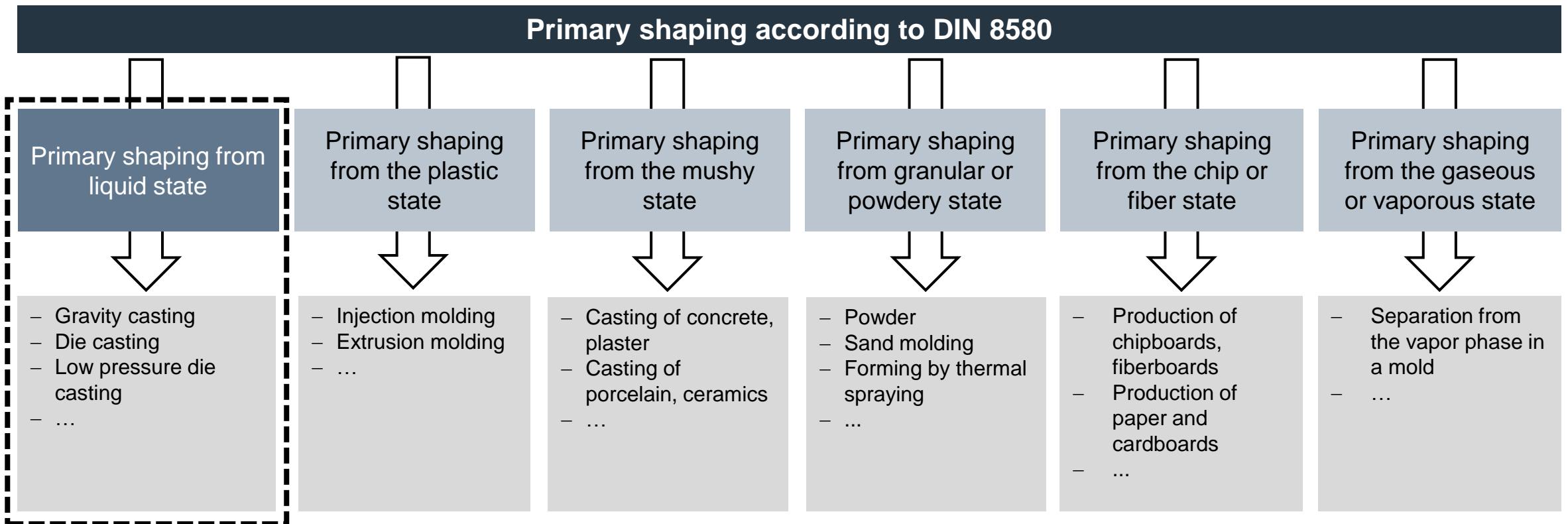
Chapter 1.1: Introduction



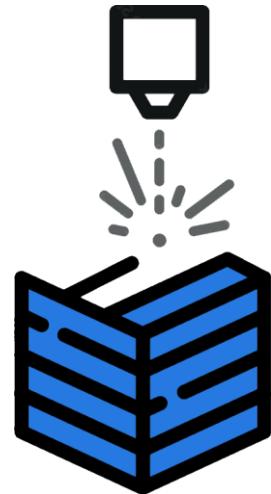
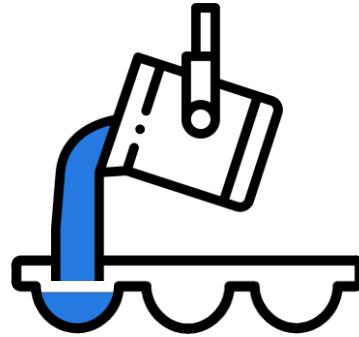
Definition of primary shaping according to DIN 8580:

"Production of a **solid body** from **shapeless material** by creating cohesion,
whereby the **material properties** of the workpiece appear in a **determinable way**."

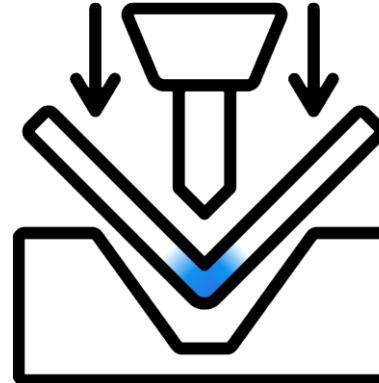
Due to the variety of sizes, requirements and materials, a large number of casting processes have been developed:



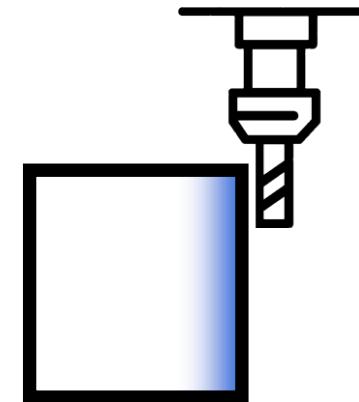
HG1: Primary Shaping



HG2: Forming



HG3: Cutting

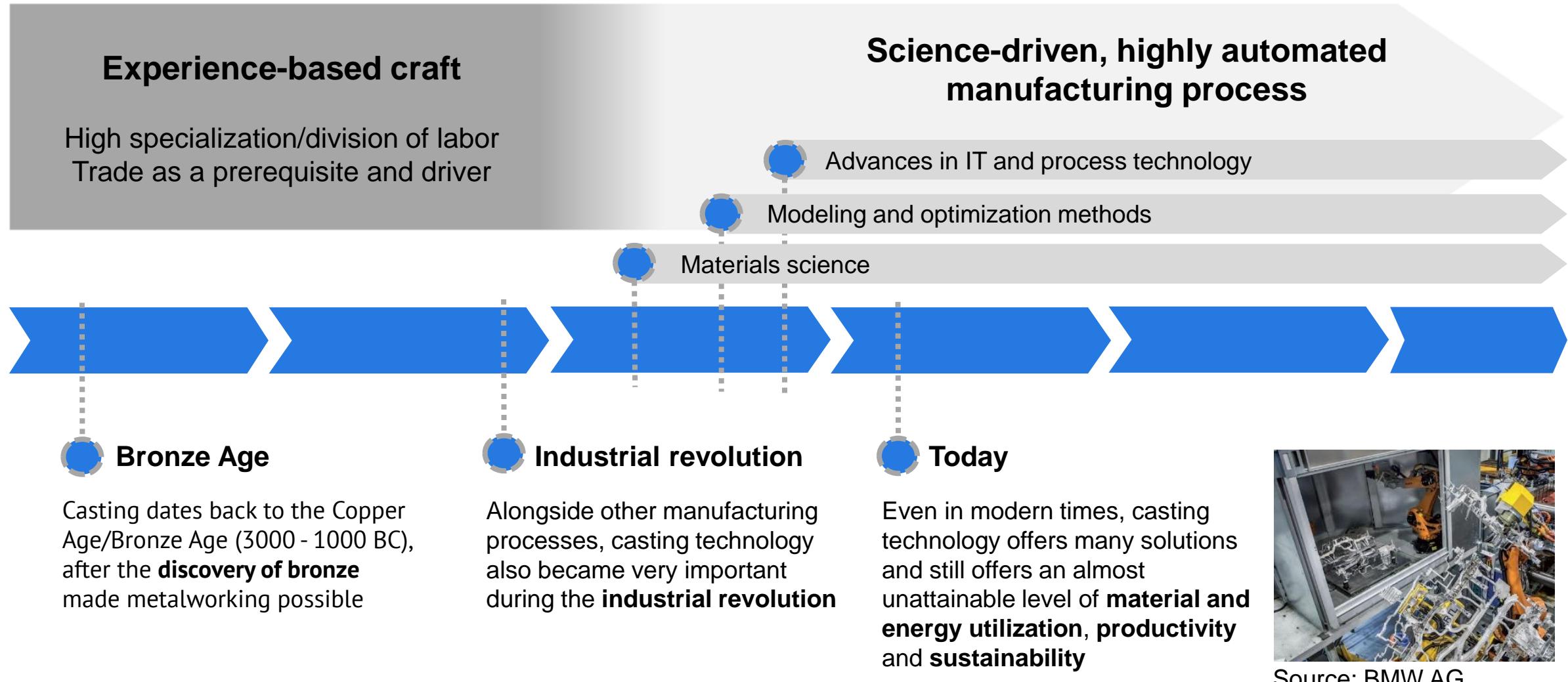


Casting (HG1.1)

Generative Technologies (HG1.10)

- Formation of a **full solid body** from the **liquid phase** (HG1.10: also, the gaseous phase is involved)
- **All areas** of the solid body are **affected** by the manufacturing process
- Mechanical properties and defects of the solid body (cracks, pores) are significantly influenced by the characteristic cooling rates during **solidification**

- **Solid phase** processes
- **Localized** highly **plastic deformation** of material areas, high deformation speeds
- **Localized temperature influence** on material areas as a result of the manufacturing process, e. g. plastic deformation



Introduction

Spectrum of casting processes



Casting of a ship's propeller, Mecklenburger Metallguss GmbH

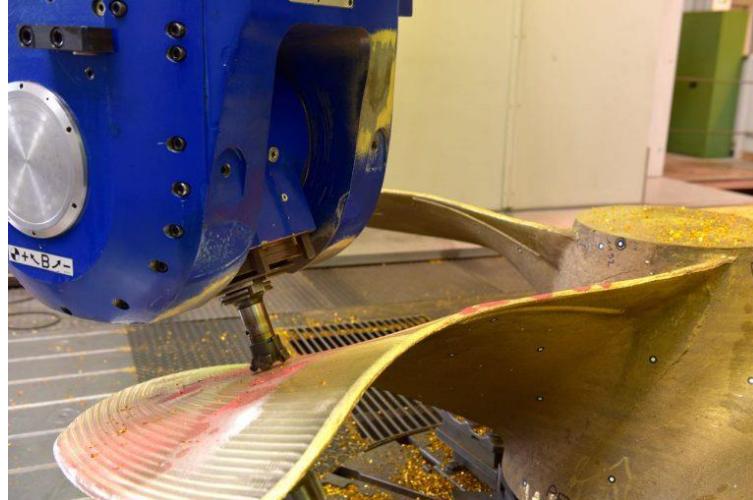


Robot-based manipulation and measurement of a light metal die-cast component, BMW AG

- **Wide range of different casting processes** and associated components (dimension, alloy, quantity)
- On the one hand, manual casting processes for highly individualized components (quantities 1-10), on the other hand, highly automated casting processes for quantities > 1,000,000 components

Introduction

Necessary post-processing and quality assurance



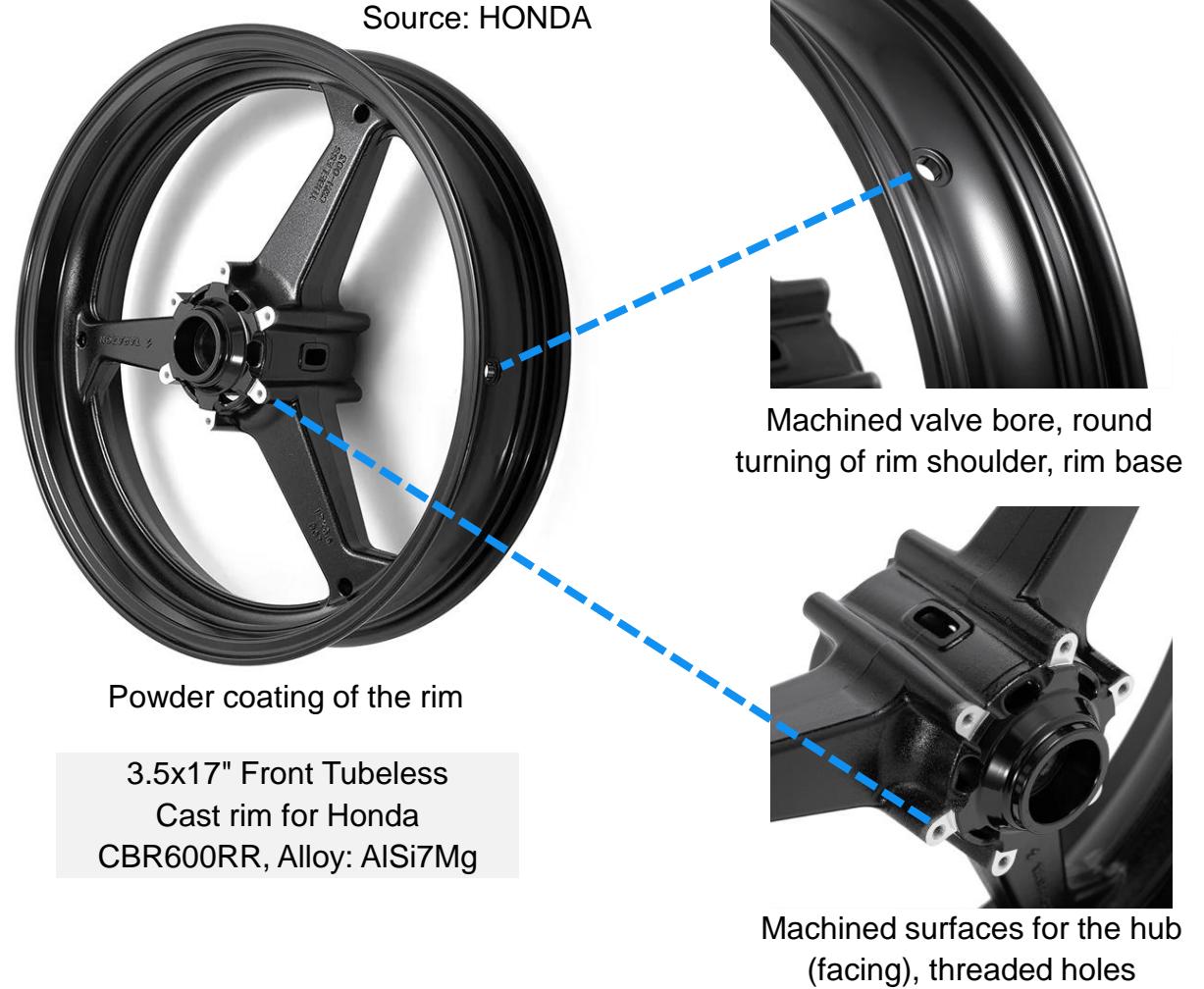
Machining and 3D component measurement of a ship's propeller, Mecklenburger Metallguss GmbH

- The production of cast components is a complex process that goes beyond simply casting the material
- **Post-processing and quality assurance** processes are crucial to ensure the functionality and reliability of the cast components and to meet the required standards of the industry or end customers
 - **Machining:** Usually necessary to achieve the required tolerances or surface finishes
 - **Heat treatment:** Improves the mechanical properties of the workpiece, such as hardness and toughness, but also serves to homogenize material properties
 - **Quality assurance:** A variety of test procedures to ensure that the component meets the specifications, e.g. 3D component measurement to check the geometric dimensions and measurement of (surface) roughness

Introduction

Example of the use of different manufacturing processes for cast components

- In relation to the realization of a cast component, processes of different main groups (“*Hauptgruppen*”, HG) of production technology according to DIN 8580 are often used:
 - **HG1:** Primary shaping (→ Casting process)
 - **HG6:** Change material properties (→ Heat treatment of the component)
 - **HG3:** Cutting (→ Machining/final contouring of the component)
 - **HG5:** Coating (→ Decorative painting of the component, anti-corrosion coatings)
 - **HG4:** Joining (→ Creating a welded assembly, screwing, bonding)

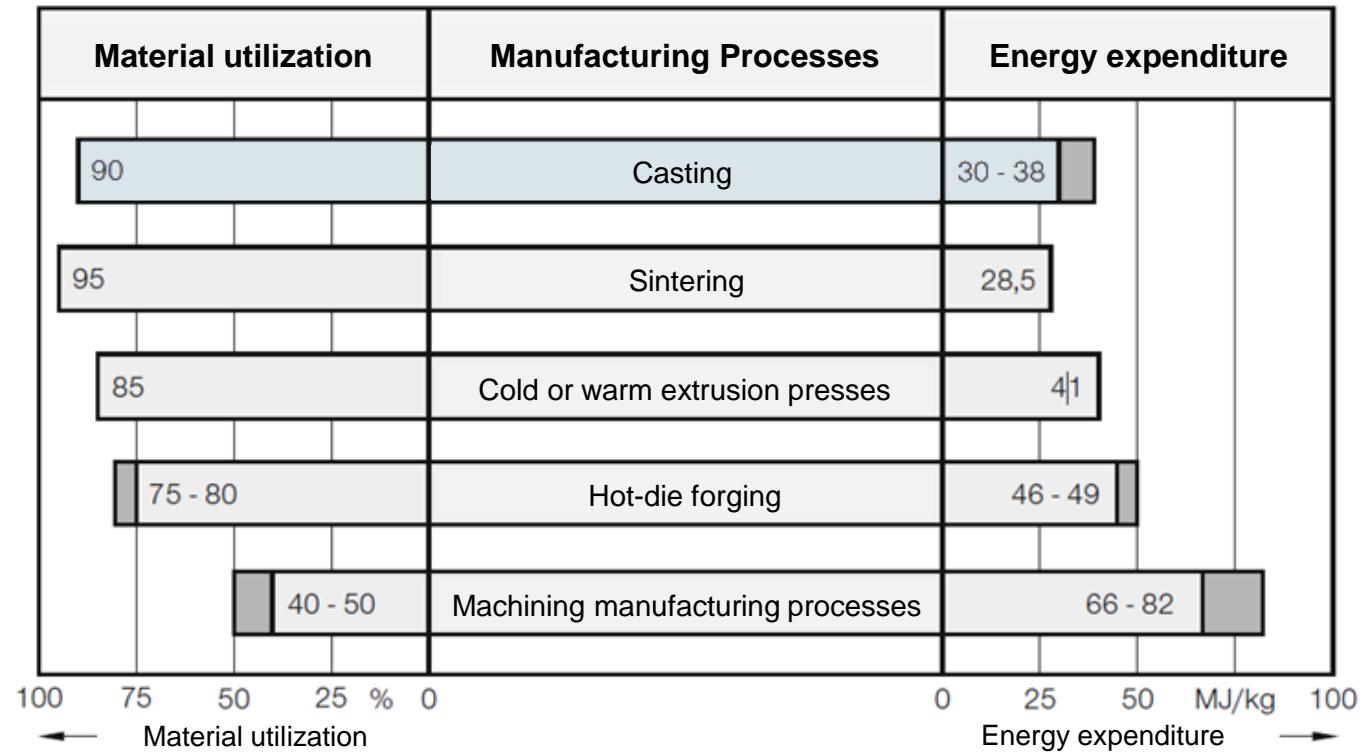


Introduction

Comparison of material utilization and energy efficiency

- **Material utilization** and **energy efficiency** are key aspects when selecting manufacturing processes, especially for large quantities
- **Material utilization:** Generally high material utilization, as the material is poured in liquid/partially liquid form into a near-net-shape mold → complex geometries can be produced using as little material as possible
- Casting processes are in contrast to ablative processes such as milling, where a large proportion of the raw material ends up as chips or waste
- **Energy efficiency:** on the one hand, the melting of metals is energy-intensive; on the other hand, the direct production of complex parts in a single step can enable energy savings compared to multi-stage manufacturing processes

[FRI08]



Introduction

Industry key figures

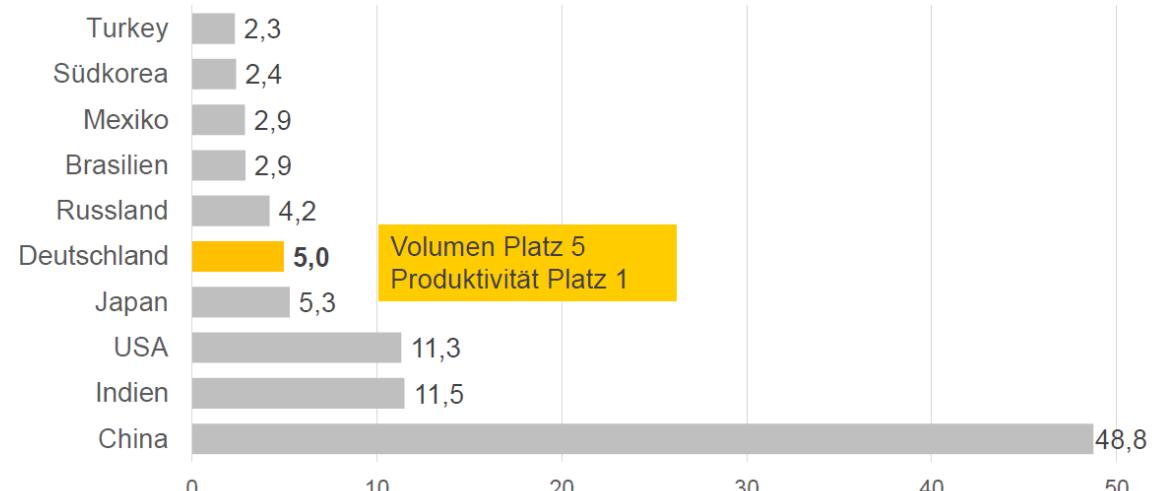
Key figures for the German foundry industry, 2020

	Produktion	Umsatz	Beschäftigte
Gesamt	3,484 Mio. t - 28 %	10,176 Mrd. € - 18 %	68.000 Mitarbeiter - 10 %
Fe	2,715 Mio. t - 29 %	5,465 Mrd. € - 21 %	35.400 Mitarbeiter - 11 %
NE	0,769 Mio. t - 25 %	4,711 Mrd. € - 15 %	32.500 Mitarbeiter - 9 %



Usually differentiation between iron (Fe) and non-ferrous (non-ferrous: Al, Cu, Mg, Ti etc.)

Global ranking of foundry industry production (in million tons), 2019

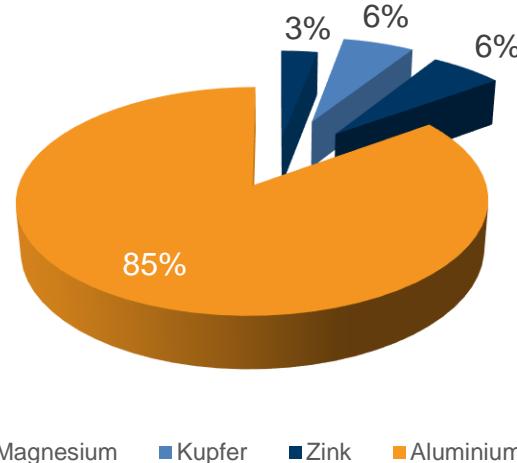


Introduction

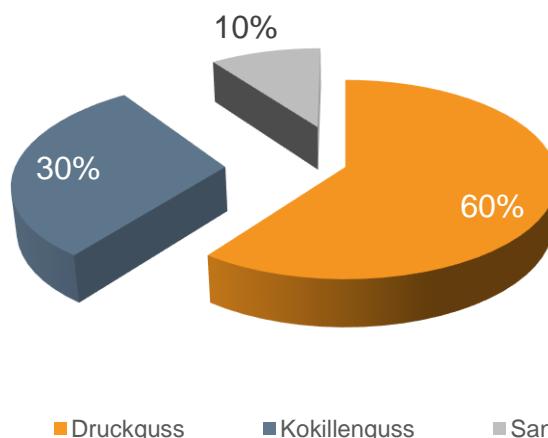
Industry key figures

- Alongside iron alloys, aluminum is one of the most important basic alloying elements
- The majority of applications for aluminum alloys are still found in road vehicle construction

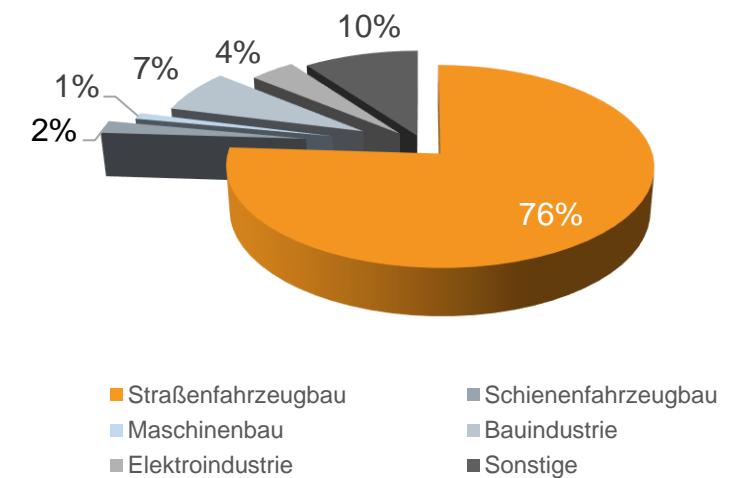
Material structure of non-ferrous metals



Shares of casting processes for non-ferrous metals



User structure of Al alloy



Source: Branchenkennzahlen 2020 - Deutsche Gießerei-Industrie, Bundesverband der Deutschen Gießerei-Industrie (BDG)

Introduction

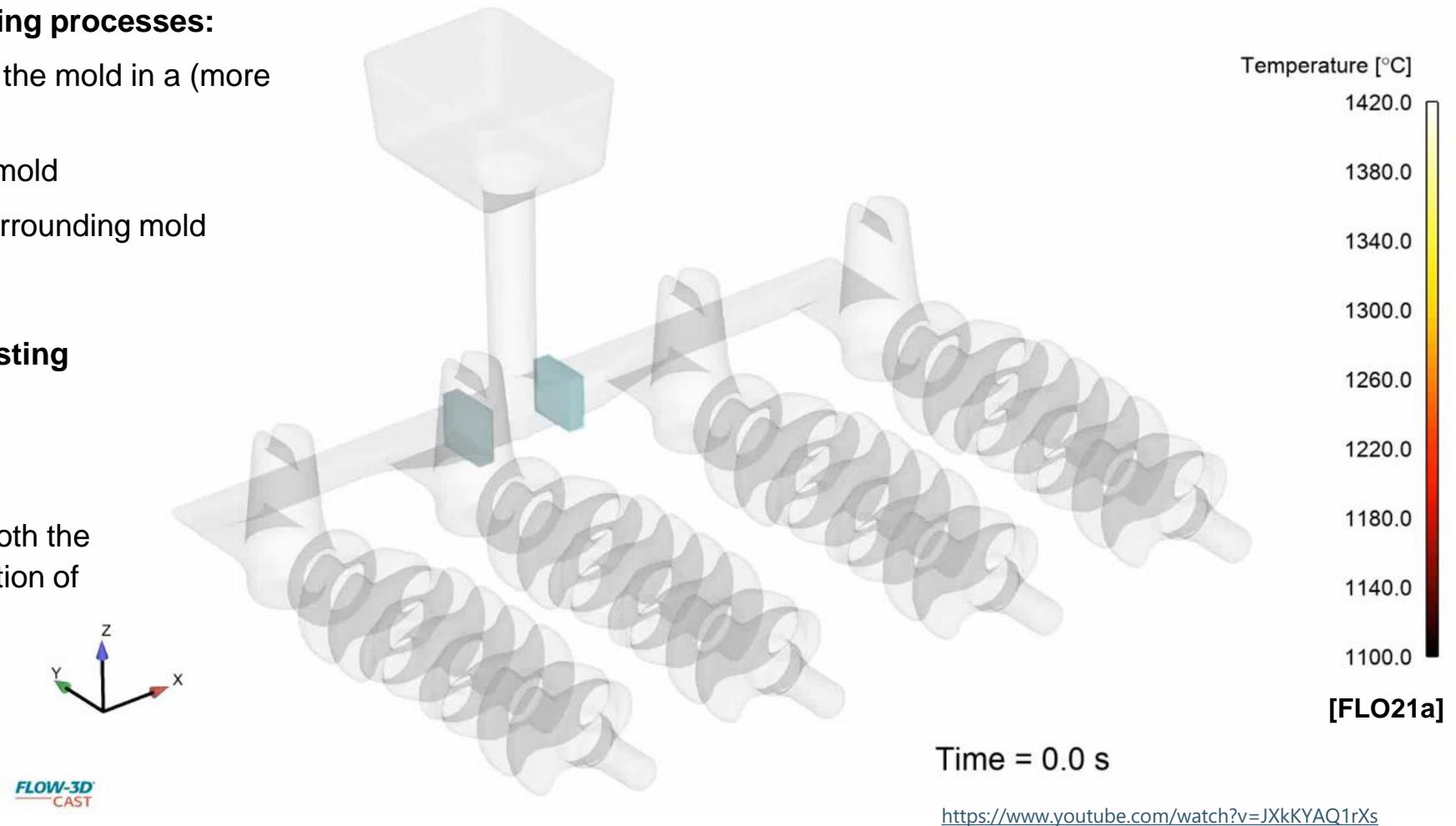
The casting process for molten metal

Aspects of the description of casting processes:

- The casting material is **filled** into the mold in a (more or less) liquid state
- **Solidification** of the alloy in the mold
- Required **demolding** from the surrounding mold

Casting simulation of a gravity casting process:

- Visualization of mold filling and solidification of the filled melt
- After completion of mold filling, both the temperature and the volume fraction of the melt (f_{Liquid}) decrease



The **melt** must

- be transported into the existing mold,
- fill the desired mold completely before it solidifies,
- remain liquid for as long as necessary, but solidify as early as possible,
- provoke as little turbulence/air inclusions as possible during mold filling



Physical principles of action to be mastered::

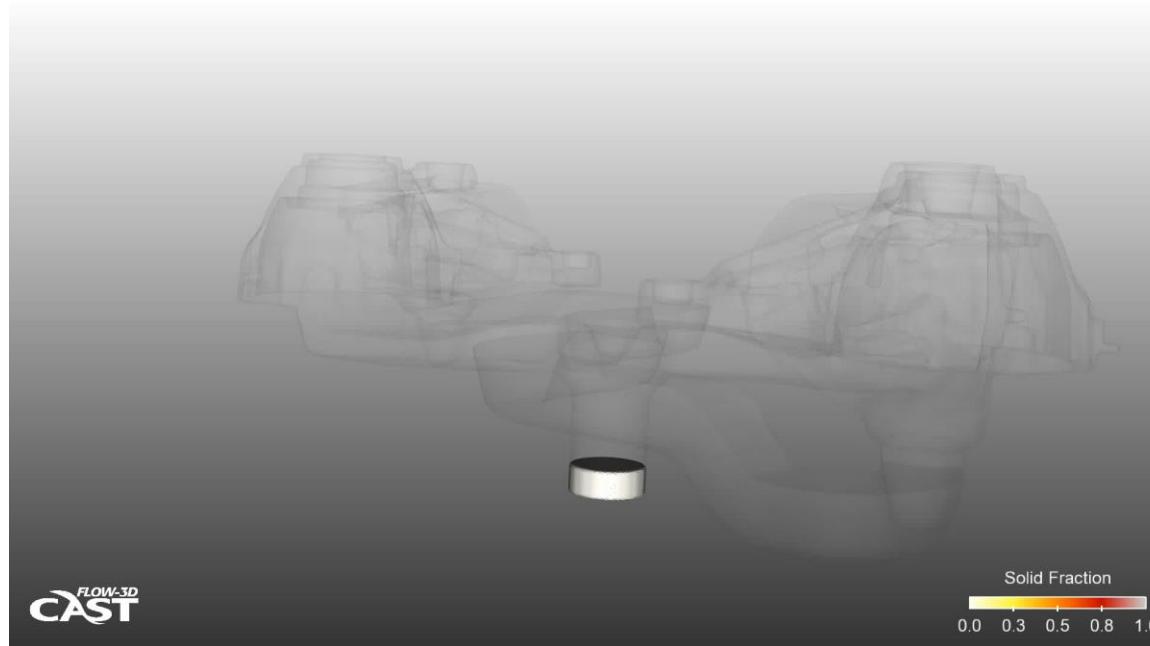
- **Acceleration** of the melt (application of pressure/force)
- Generation and control of a sufficient mold filling speed
- Control of the **temperature** of the melt and mold,
heat dissipation
- Possibility of describing and designing a **fluid flow**
- Molding properties, design



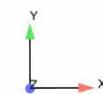
The **cast component** must be demolded again after the casting process

Introduction

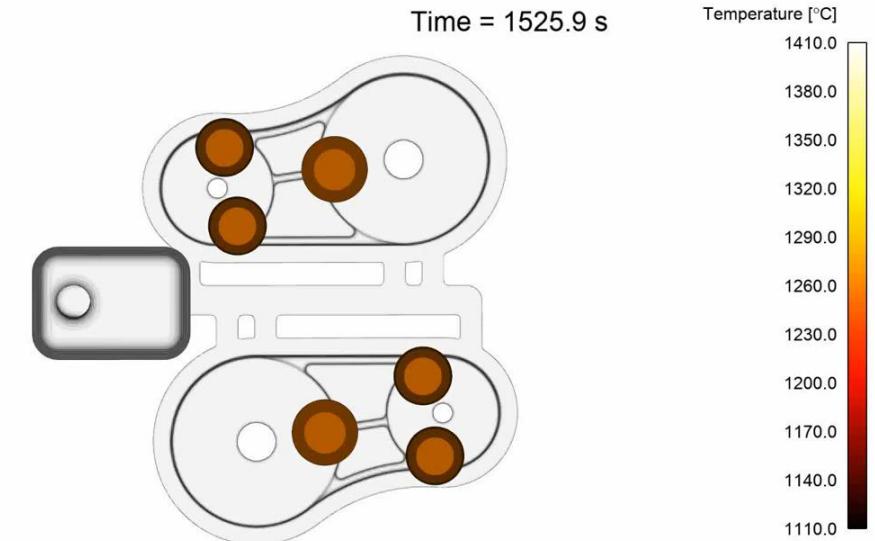
Visualization of different casting processes



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CAST



GRAVITY SAND CASTING

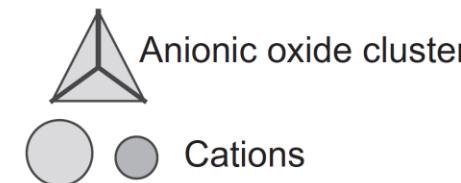
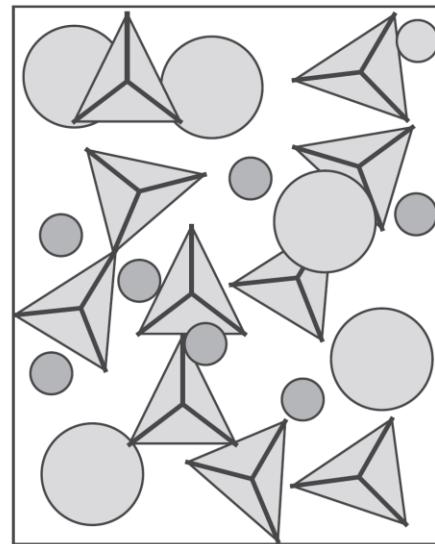
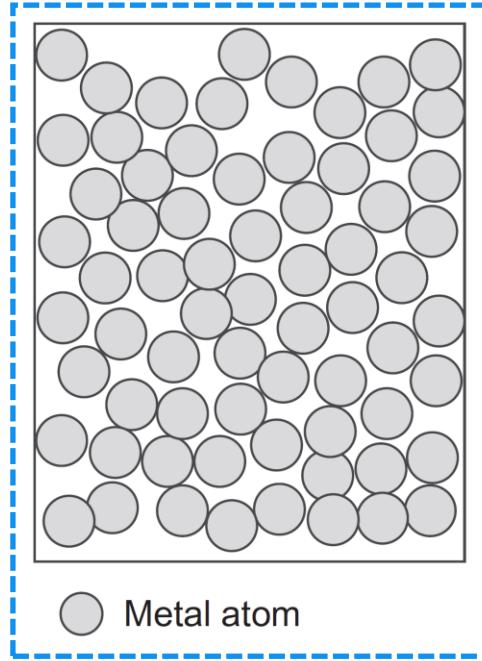


- Rising casting process (gravity die casting process) - pressurization of the melt required
- Visualization of the **solid fraction** (f_{Solid})
- Mold filling-related casting defects become visible
- Gravity-based casting process (sand casting)
- Visualization of the **melt temperature**
- The additional elements of a casting system (e.g. filter, riser) to ensure sufficient component quality become visible

Chapter 1.2: Crystallization

Crystallization

Schematic structures of liquids: metal, ceramic glass and thermoplastic polymer



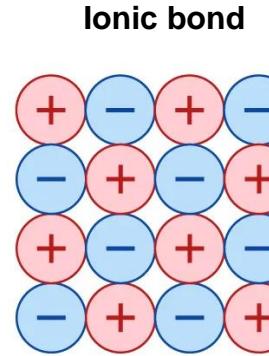
The schematics are not to-scale and include more free space than would be present in the real liquids!

Initial state of liquid metals:

- Molten metals are composed of a **disorganized array of spherical atoms in thermal motion**
- Both **attractive and repulsive interactions** between adjacent atoms, as in solids, but interatomic separations are larger than in solids and the interactions weaker
- The **attractive interactions** that hold the **liquid** together are mainly **electrostatic**, similar to those in solid metals
- The ion cores of metallic atoms are attracted to the surrounding sea of electrons
- **Metal alloys**, which are composed of more than one type of metal atom, have **more complex structures** and interatomic bonds
- Clusters of atoms may form in the liquid state

Crystallization

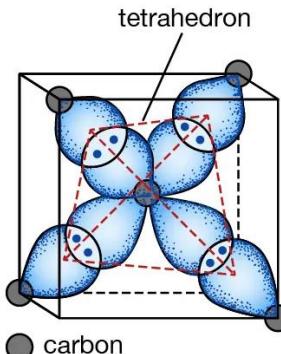
Chemical bonding in crystalline solids



An idealized ionic (or electrovalent) bonding of oppositely charged ions.

Sodium Chloride (NaCl), MgO

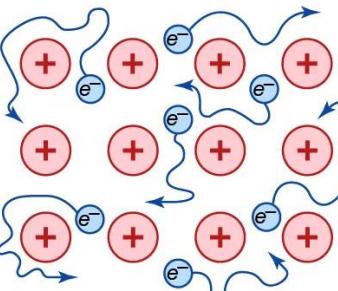
Covalent bond



Covalent bonds involve electron sharing, such as between these carbon atoms when they form a diamond.

Diamond structures

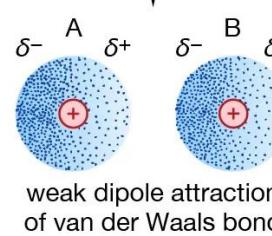
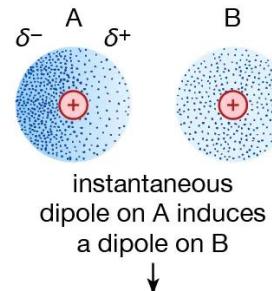
Metallic bond



metallic structure, showing possible electron (e^-) paths around the nuclei of metal atoms (represented as spheres with a positive charge)

Metallic bonding can be thought of as a cloud of positively charged ions immersed in a cloud of valence electrons.

van der Waals bond



Neutral molecules may be held together by a weak electric force known as the van der Waals bond.

Aluminium, Copper, Iron

Graphite, Noble Gases

Metals: Metallic bonds

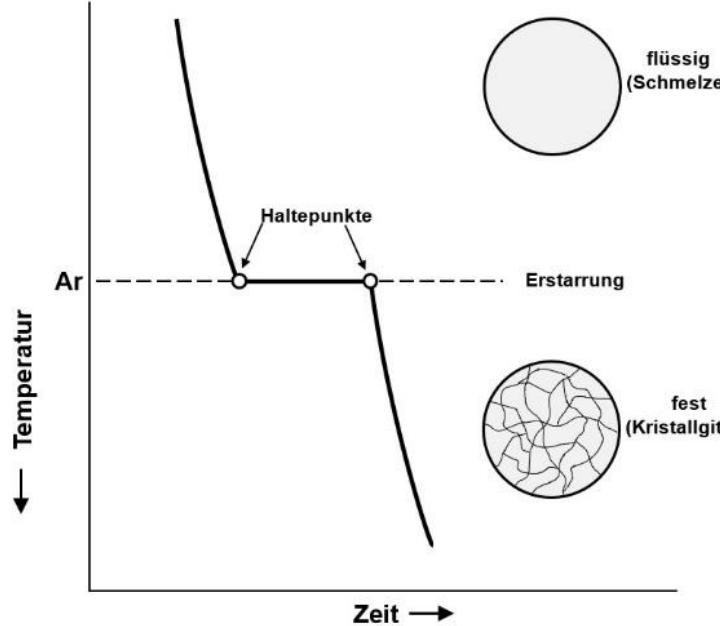
Ceramics: Ionic and covalent bonds

Plastics: Covalent and Van der Waals bonds

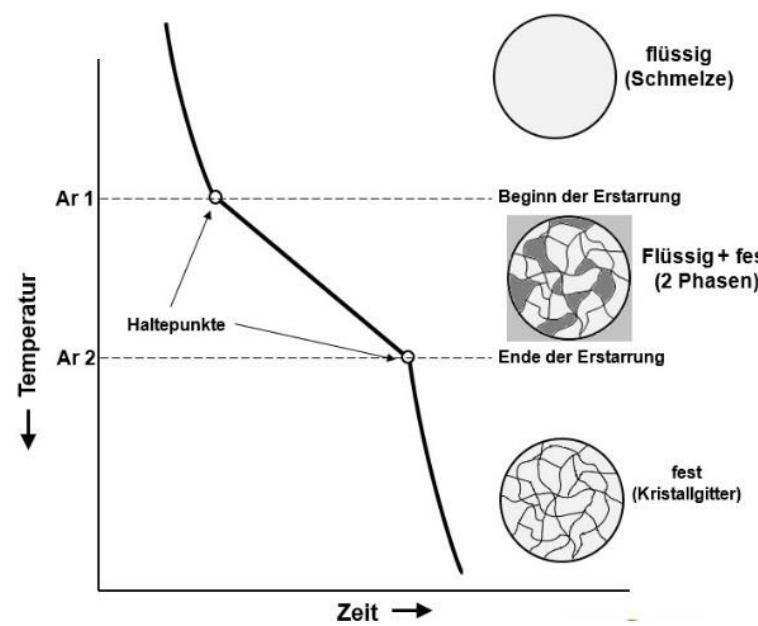
- The ion cores of **metallic atoms** are attracted to the surrounding cloud of valence electrons
- Molten metal structure and properties change with temperature
- As the **temperature is raised**, **atomic vibrations and motions increase**, atoms are driven further apart and interatomic bonds weaken → the **density of the melt drops** consequently
- In contrast, as the **melt temperature decreases**, the reverse occurs until the **melt crystallizes** and the **atoms become locked into the regular crystal structure** of the solid

Crystallization

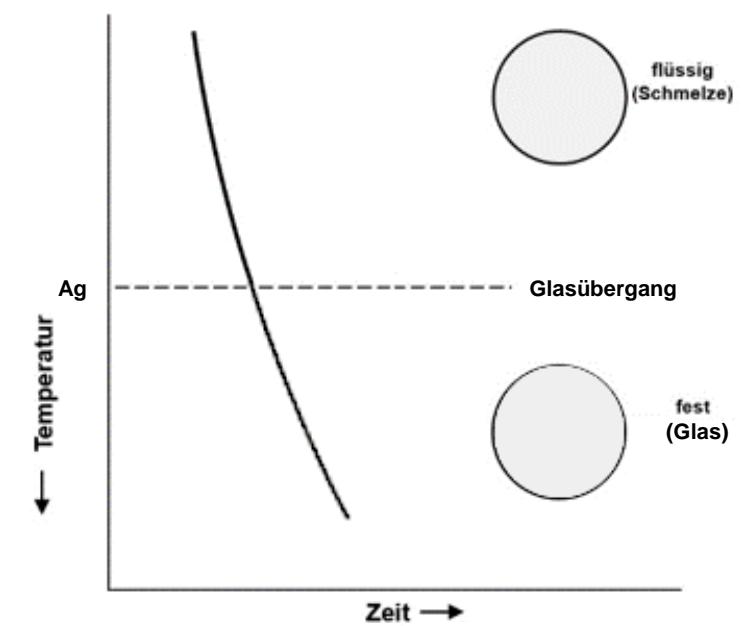
Temperature-time curves during the cooling of metals



Temperature profile of a **pure metal** during solidification



Temperature profile of an **alloy** during solidification



Temperature profile of a **glass** during solidification

Crystallization – heat release

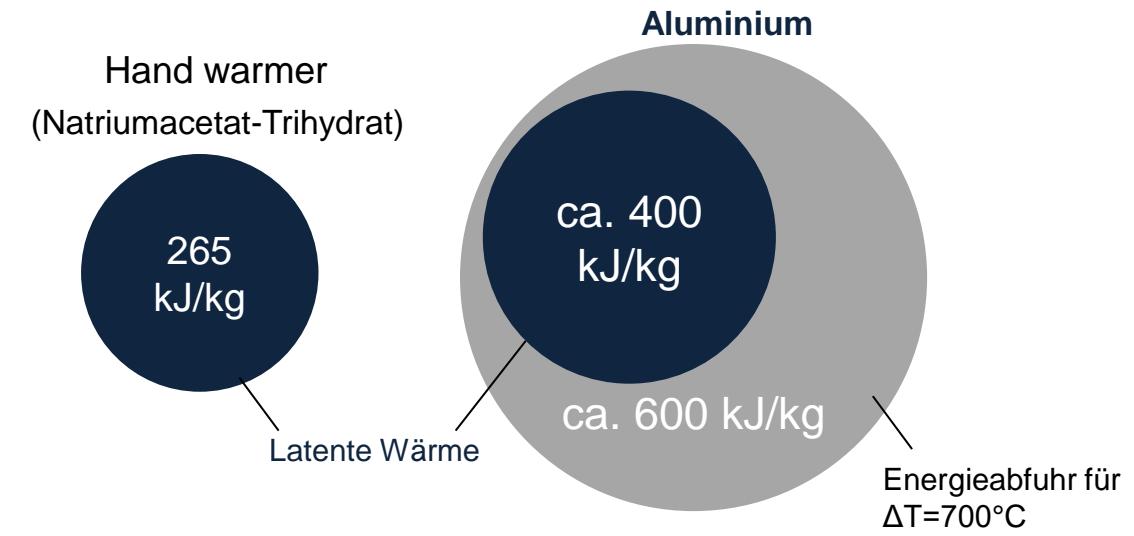
Freezing of the melt

No heat release

Crystallization

Heat release during solidification

- When a melt solidifies, the **heat transport** usually determines the speed of the process
- During solidification, very large amounts of heat of fusion H (or here: L) are released, which must be dissipated
- For materials at melting temperature, the heat of fusion typically reaches the same order of magnitude as the value of the integral $c_p dT$



Melting temperature and heat of fusion of some substances:

Z	Größe	Al	Si	Fe	Cu	Al_2O_3	H_2O
1	T_S (K)	933	1683	1808	1356	2303	273
2	T_S (°C)	660	1410	1535	1083	2030	0
3	ΔH_S (kJ/mol)	10,5	50,7	15,1	13,0	109	6
4	ΔH_S (J/g)	404	1640	270	205	255	334
5	$\Delta H_S/RT_S^a$	1,35	3,62	1,00	1,15	5,69	2,64

Atomic masses

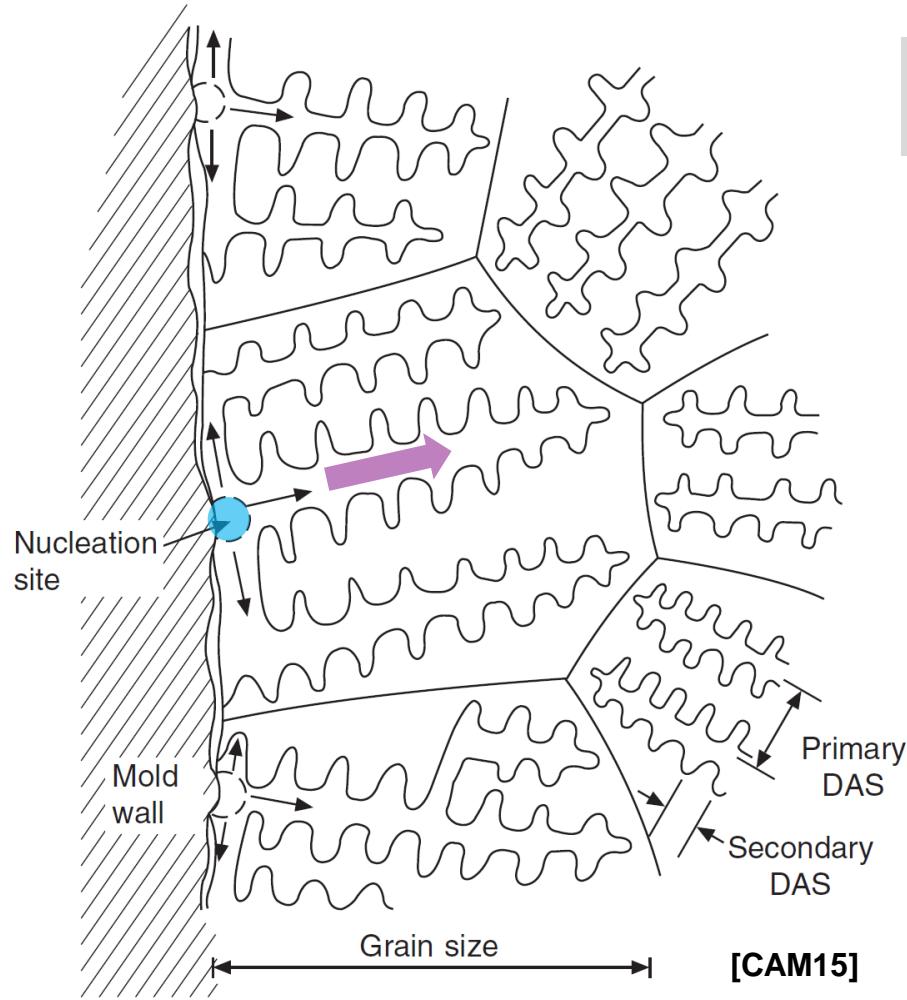
Al: 26,981539 u

Si: 28,0855 u

$$\rightarrow \Delta H_{S,\text{Al}} = 10,5 \text{ kJ/mol} \leftrightarrow 389 \text{ J/g}$$

$$\rightarrow \Delta H_{S,\text{Si}} = 50,7 \text{ kJ/mol} \leftrightarrow 1805 \text{ J/g}$$

[SIN16]



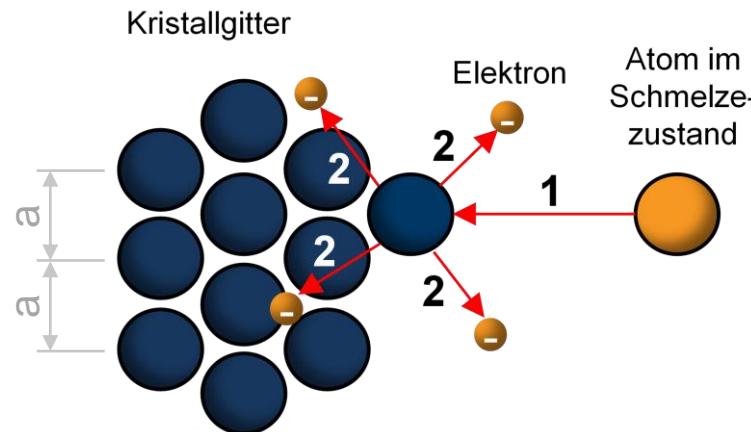
Crystallization is a process in which atoms, molecules or ions are arranged in an ordered, solid structure that permeates the entire solid.

- **Nucleation:** First step in which small solid clusters are formed from the liquid; two types: homogeneous/heterogeneous
- **Crystal growth:** Nucleation sites as the starting point for crystal growth; molecules arrange themselves on nuclei and form the specific pattern of the crystal
- The rate of growth and thus crystal properties vary depending on the orientation of the crystal surface and are influenced by **temperature, concentration and impurities**
- **Interaction of crystal growth**
- Growing crystals can fuse when they meet others, reducing the number of crystals but increasing the size (known as coarsening or Ostwald ripening)
- Process continues until the liquid is completely solidified or equilibrium is reached with the solid (e.g. in eutectic systems)

- Temperature below melting point: The thermal movement of the individual atoms is so low that the mutual bonds can no longer be broken by vibrations
→ **Decrease in the kinetic energy** of the atoms and **binding to a stable and ordered crystal lattice**
- During integration into the crystal lattice, the **electrons are separated** from the atomic nucleus and **collide** with other atoms and electrons
- The **latent heat** refers to the energy released during the phase transition without changing the temperature
- During crystal formation, **diffusion processes** occur continuously in which atoms in the molten state encounter an existing crystal lattice

Long-distance order:

regular and continuous
endless (into the distance)
arrangement of molecules
or atoms in a crystalline
solid

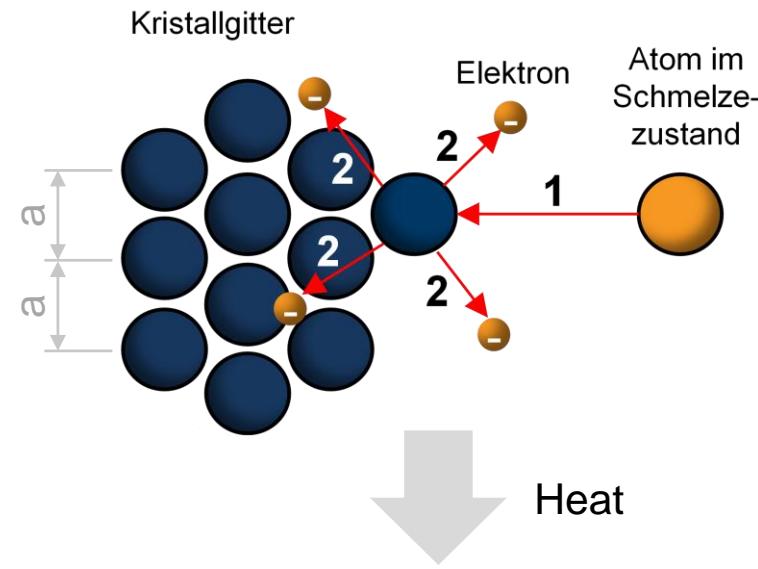


Crystallization process at the atomic level:

- Through **diffusion processes**, an atom in the molten state encounters the existing crystal lattice
- The electrons are separated from the atomic nucleus and collide with other atoms and electrons (→ latent heat) due to **integration into the lattice** (Long-distance order)

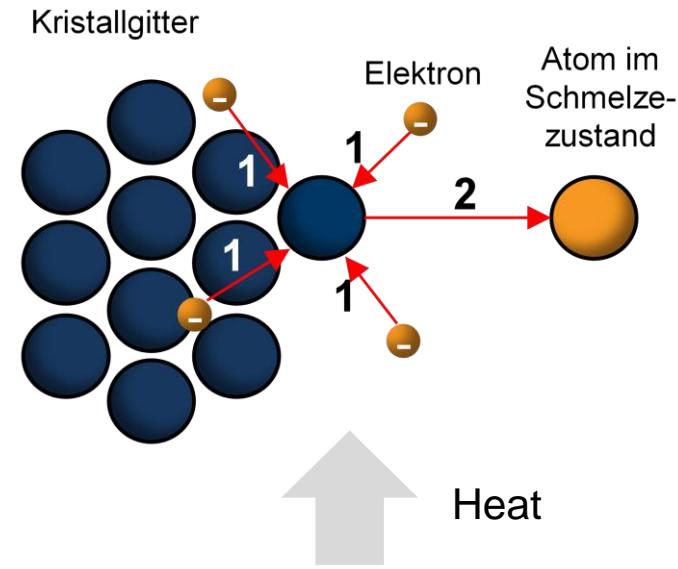
Exothermic process

Crystallization: Incorporation of an atom into a uniform, regular lattice



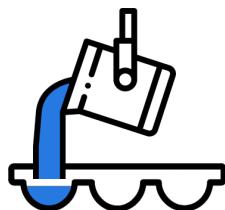
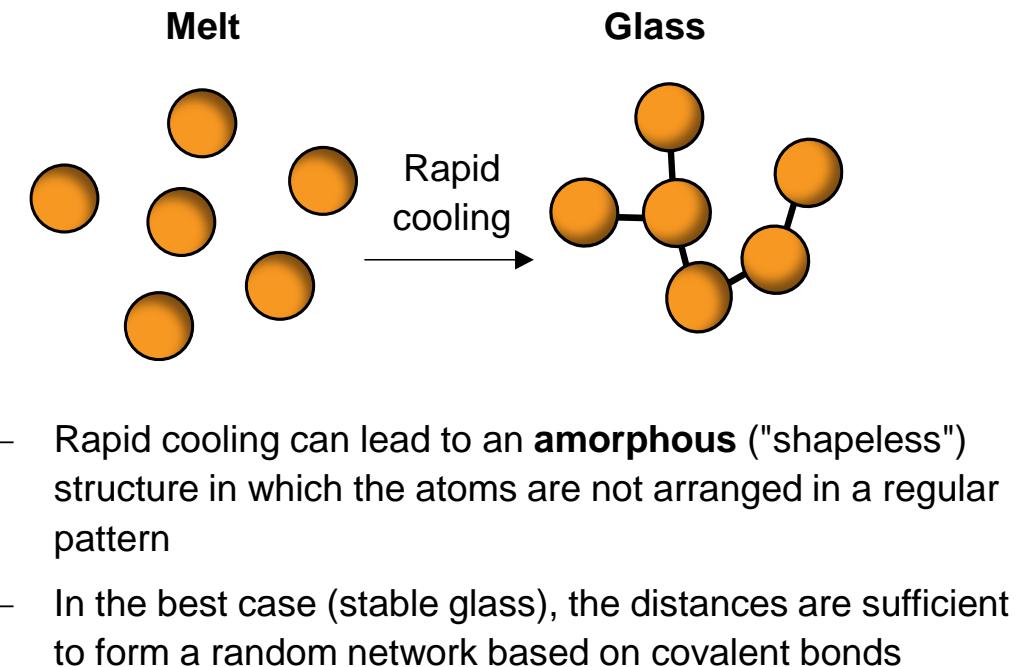
Endothermic process

Melting: Removal of atoms from the long-distance order



Crystallization-free solidification

- **Kinematic inhibition of diffusion processes** through rapid cooling
 - Atoms have too little kinetic energy due to the rapidly falling temperatures to reduce the distances to each other so much that crystallization can occur
- If solidification is sufficiently rapid, the required maximum distances between the atoms are not reached
- **Electrons are not delocalized**, i.e. they cannot dissipate energy through collisions as they are still bound to the atom
- **Without crystallization** (= delocalization of the electrons) **no latent heat** and therefore no heat development during solidification

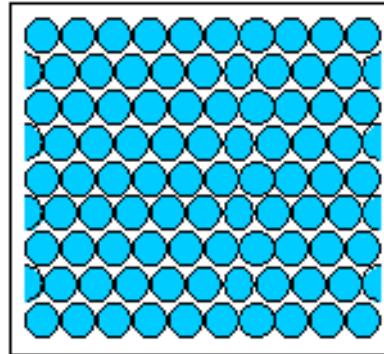


In **casting processes**, however, **crystalline structures** are almost always present. This is due to the **cooling rates** that can be achieved in practice and the **alloy composition** of conventional metallic materials.

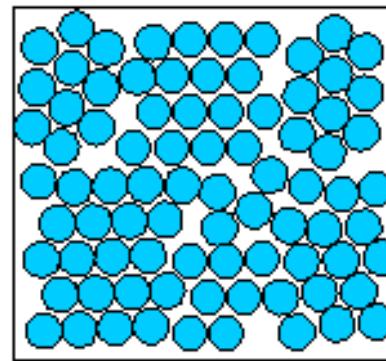
Crystallization

Single crystal ↔ Polycrystal

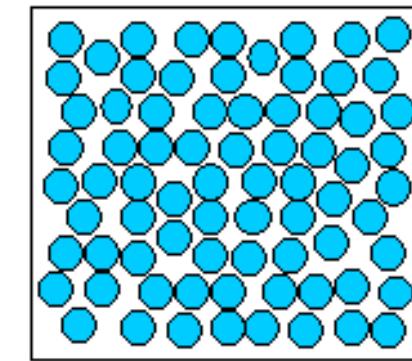
- The fundamental difference between **monocrystalline (single crystal)**, **polycrystalline** and **amorphous** solids is the length scale over which the atoms are connected in a regularity (→ "periodicity" or "long-range order")
- Single crystals have infinite periodicity, polycrystals have local periodicity, and amorphous solids (and liquids) have no long-range order



Single crystal
Periodic across the
whole volume.



Polycrystal
Periodic across
each grain.



Amorphous solid
Not periodic.

Ideal single crystal:

- Atomic structure that repeats **periodically** throughout its volume

Polycrystal:

- Composition of many **individual grains or crystallites**
- Each grain can be considered as a single crystal in which the atomic structure exhibits long-range order
- On a sufficiently large length scale, **no periodicity** in a polycrystalline sample

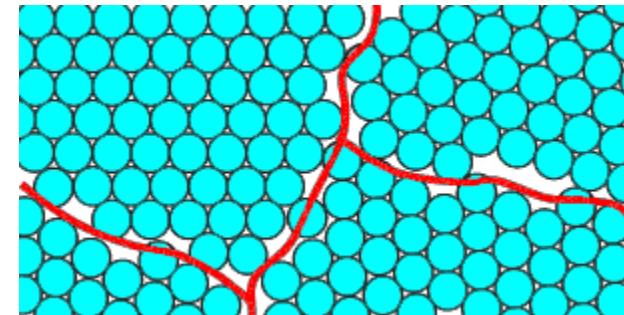
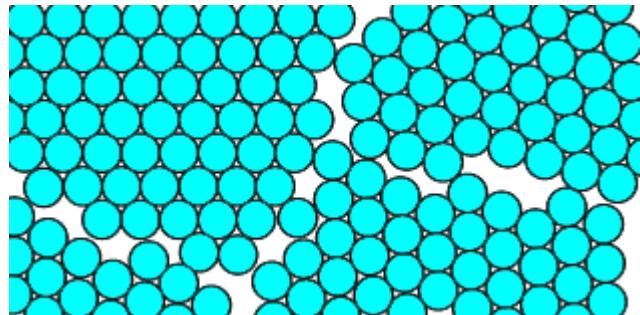
Amorphous materials:

- **No long-range order** at all
- The distances between the atoms in the structure are precisely defined and are similar to those in the crystal (long-range order but only in crystals)

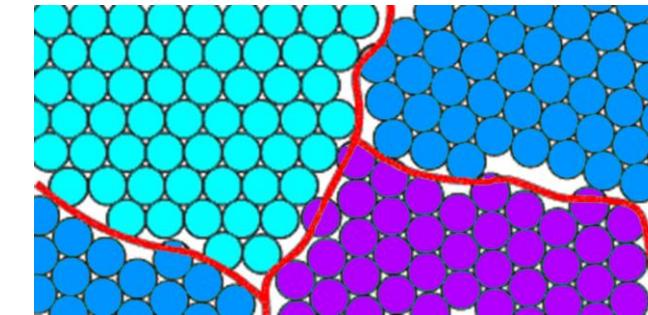
Source: University of Cambridge, Dissemination of IT for the Promotion of Materials Science (DoITPoMS)

Lattice defect

- A real crystal contains **lattice defects** → the three-dimensional periodic **arrangement of the atoms** is **disturbed**
- Differentiation with regard to point errors, line errors, area errors and volume errors
- As a rule, a **crystalline solid** is present as a **polycrystal** → Body consists of many small crystals that are separated from each other by **grain boundaries**
- If **different types of crystals** are present next to each other → **Phase boundaries**



Crystalline regions (grains) of a polycrystal that are bounded by disordered **grain boundaries**



Crystalline regions of a polycrystal that are bounded by disordered **phase boundaries**

Source: University of Cambridge, Dissemination of IT for the Promotion of Materials Science (DoITPoMS)

Chapter 1.3: Speed of transformations

Speed of transformations

Transformation rate/precipitation rate dW/dt

Crystallization is the combined process of *nucleation* and *growth* that transforms a liquid into a crystalline solid.

The transformation rate/precipitation rate dW/dt depends on how many nuclei have formed and the speed at which the phase interfaces move:

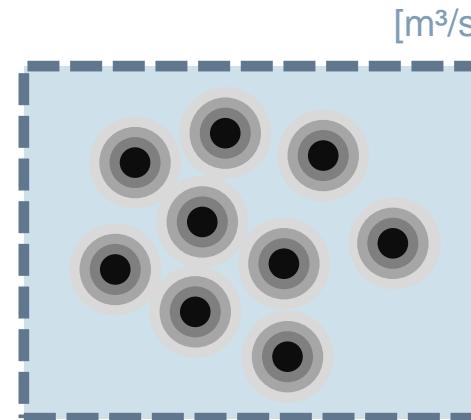
$$\frac{dW}{dt} = N(t) \cdot A(t) \cdot v(t) \quad \text{Eq. 1.3.1}$$

with

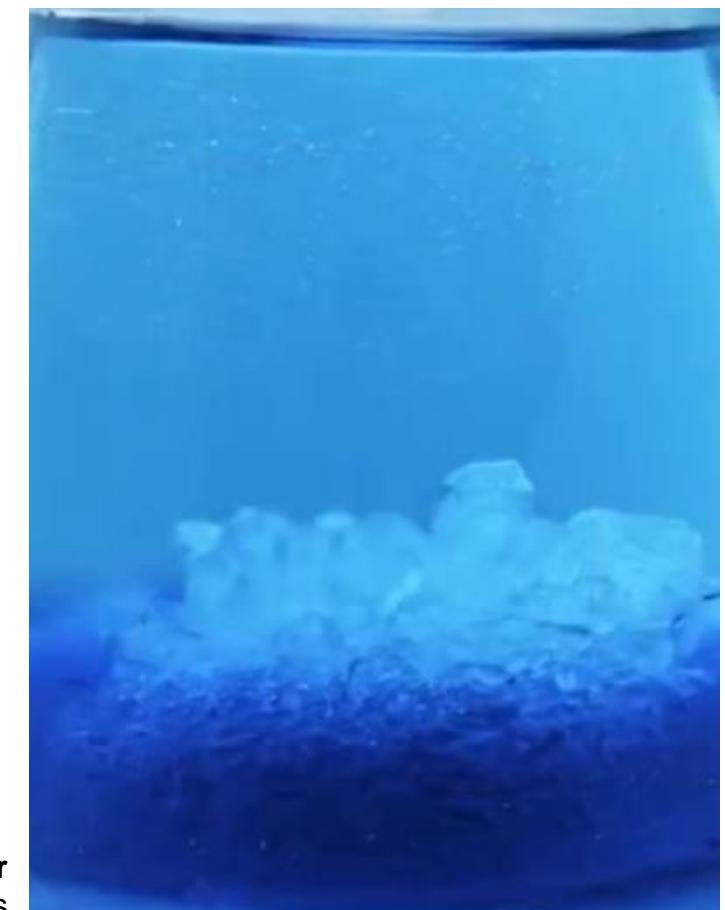
N Number of nuclei formed

A Average surface area of the nuclei in m^2

v Growth rate of the nuclei in m/s



Example of crystallization:



Fluids & Soft Matter
<https://youtu.be/B19Llx3x3as>

Speed of transformations

Influencing factors on the speed of phase transformation

Temperature gradients

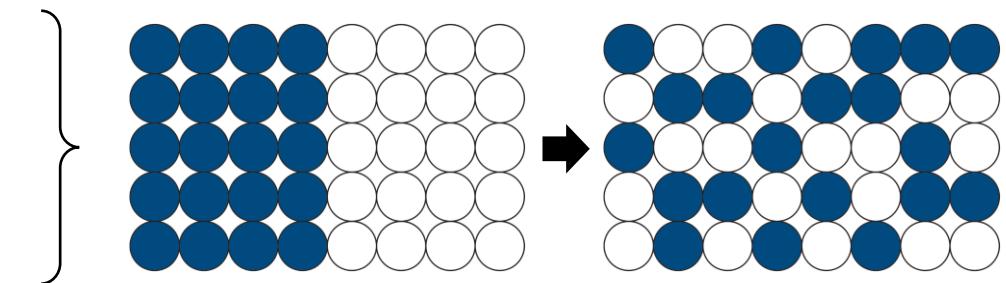
- Drives the movement of phase boundaries as different parts of the material **gain or lose energy** at different rates; **a higher temperature gradient** often results in **faster movement** of the phase interface towards the warmer region

Concentration gradients

- Non-uniform distribution of particles; the **diffusion of particles** from higher to lower concentration **increases the randomness (entropy)** of the system
- This diffusion often influences the movement of phase interfaces, as the system **moves toward a more entropically favorable** uniform distribution

Surface tensions

- Energy associated with the interface between phases; differences in surface tension **influence the shape and stability** of the phase interfaces
- Lower surface tension can lead to more rapid changes in the phase interface



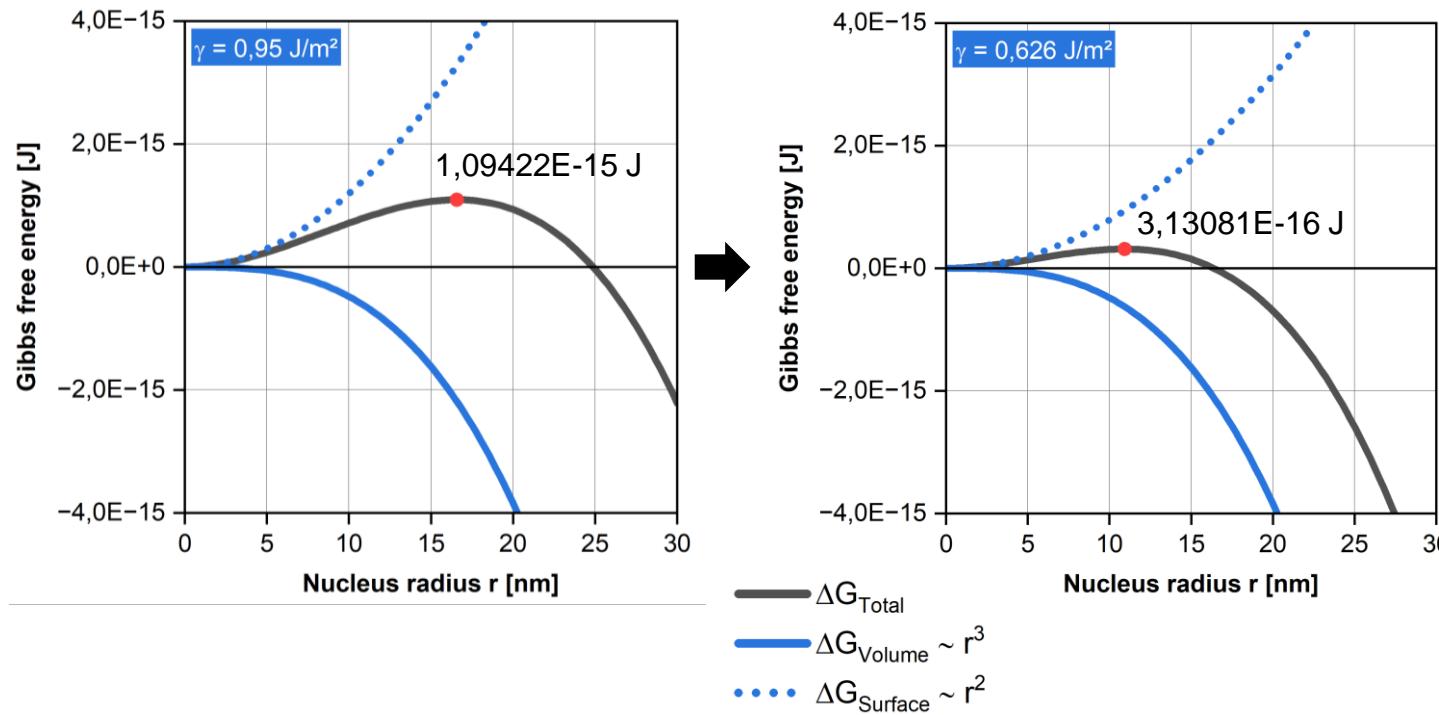
$$G_1 = X_A \cdot G_A + X_B \cdot G_B \quad G_2 = G_1 + \Delta G_{mix}$$

Schematic representation of the unmixed (ordered) and mixed (disordered) state of a two-component system

Speed of transformations

Influencing factors on the speed of phase transformation – Surface tensions

- Equation for calculating Gibbs free energy: $\Delta G_{total,hom}(r, \Delta T) = -\frac{4\pi \cdot \rho \cdot L}{3T_M} \cdot \Delta T \cdot r^3 + 4\pi \cdot \gamma \cdot r^2$ Eq. 1.3.2
- Typical values for the surface tensions (γ) of technically relevant metals are in the range between 0.2 and 2 J/m² [SIN16]
- **Lower value for the surface tension: lower Gibbs Energy, lower critical radius → higher probability for nucleation**



Measured surface tension values for pure **aluminium** under various test conditions: **0,626 .. 0,95 J/m²** according to [1]

[1] Bainbridge, I.F.; Taylor, J.A. (2013): The Surface Tension of Pure Aluminum and Aluminum Alloys. *Metall Mater Trans A* **44**, 3901–3909

Factor of ~1,5 for different **surface tensions**, factor of ~3,5 for critical **Gibbs energies** for a nucleus!

Property	Symbol	Value
Surface tension	γ	0,92 J/m ²
Density	ρ	2700 kg/m ³
Latent heat	L	396 kJ/kg
Melting temperature	T_M	660 °C

Speed of transformations

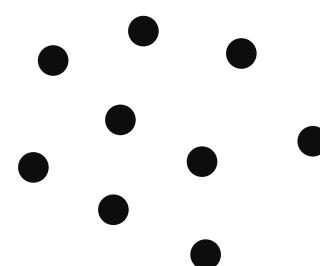
Introduction

Speed of transformation = Driving force \times Mobility of the system

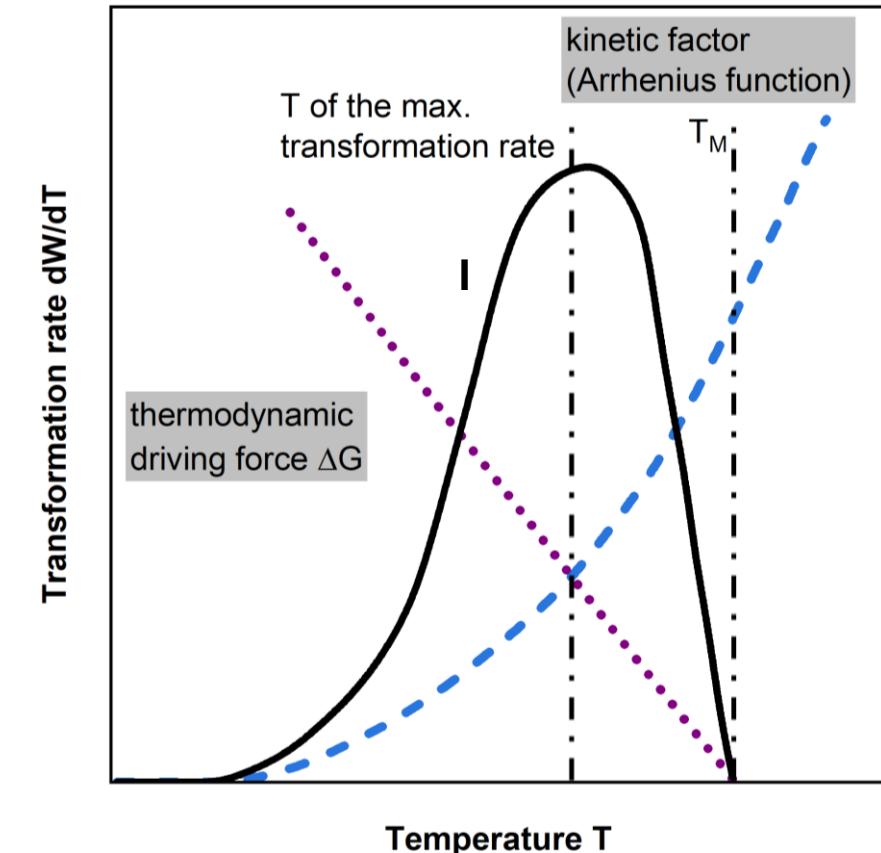
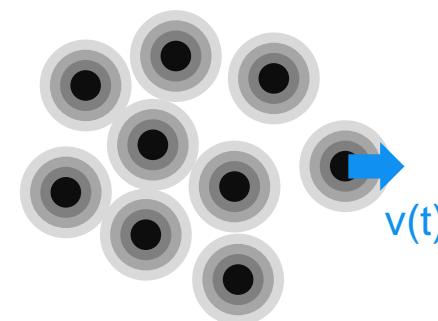
i.e., amount ΔG
between initial state
and equilibrium state

Mobility of atomic
components whose
relocation enables a
new state

**Probability of
nucleation** with a
critical energy state
 ΔG_k



Nucleus growth: In order for
the nucleus to grow, atoms
must be added through
diffusion \rightarrow Mobility term



Temperature dependence of the speed of a
transformation, considering the driving force and
diffusion-controlled nucleation growth

Speed of transformations

Definition of the nucleation rate | Driving force

Definition of the **nucleation rate I**: Defined as the number of nuclei n formed per volume and time that exceed a critical radius:

$$I = n_c \nu \quad \text{Eq. 1.3.3}$$



Concentration (number of potential nuclei per unit volume)

Frequency at which these potential nuclei become stable

Assuming that the system has a statistical distribution of core sizes, the **concentration of nuclei** with critical size is given by:

$$n_c = n_0 \exp\left(\frac{-\Delta G_k}{RT}\right) \quad [\text{Number/Volume}] \quad \text{Eq. 1.3.4}$$

with

ΔG_k Temperature-dependent activation energy for nucleation

n_0 Total concentration of atoms/molecules

 **Driving force**

Speed of transformations

Definition of the nucleation rate | Mobility of the system

Definition of the **nucleation rate I**: Defined as the number of nuclei n formed per volume and time that exceed a critical radius:

$$I = n_c \nu \quad \text{Eq. 1.3.3}$$



Concentration (number of potential nuclei per unit volume)



Frequency at which these potential nuclei become stable

To enable the nucleus to grow, atoms must be added by diffusion. The **frequency of atomic addition** results from the **diffusion of atoms** or molecules **in the melt** and is defined as follows:

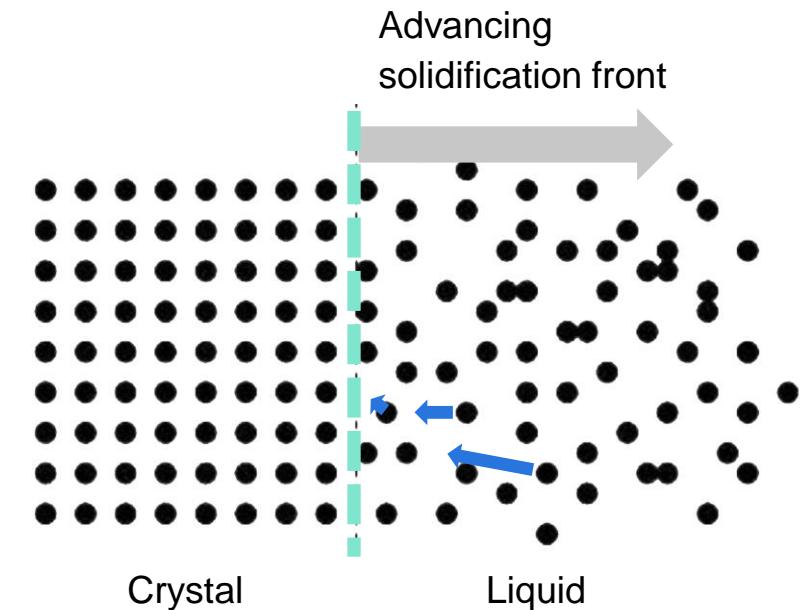
$$\nu = \nu_0 \exp\left(\frac{-Q_D}{RT}\right) \quad [1/s] \quad \text{Eq. 1.3.5}$$

with

Q_D Activation energy for diffusion

ν_0 Fundamental oscillation frequency

Mobility of the system



Speed of transformations

Nucleation rate

- A is obtained by substituting and converting n_0 and v_0 :

$$I = A \cdot \exp\left(\frac{-\Delta G_k}{RT}\right) \cdot \exp\left(\frac{-Q_D}{RT}\right) \quad \text{Eq. 1.3.6}$$

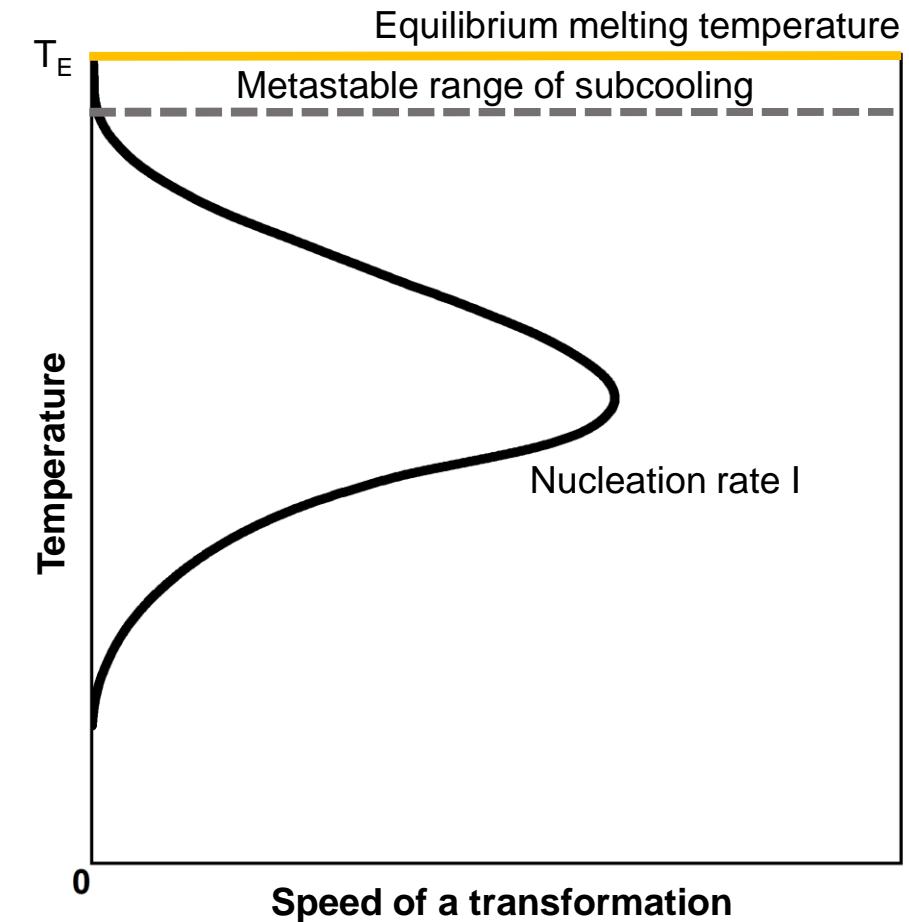
Driving force term increases
with increasing undercooling

Nucleation

Mobility term decreases with
increasing undercooling

Nucleation growth

- At melting temperature T_M , there is no thermodynamic driving force for nucleation → nucleation rate is zero
- If the temperature decreases, $-\Delta G_k$ becomes an increasingly large negative number and **ΔG decreases**, so that the **concentration of nuclei of critical size increases**
- At the same time, however, the **frequency of addition of atoms or molecules to the critical nucleus decreases**
- These competing effects lead to a **peak in the nucleation rate** at a temperature below T_M

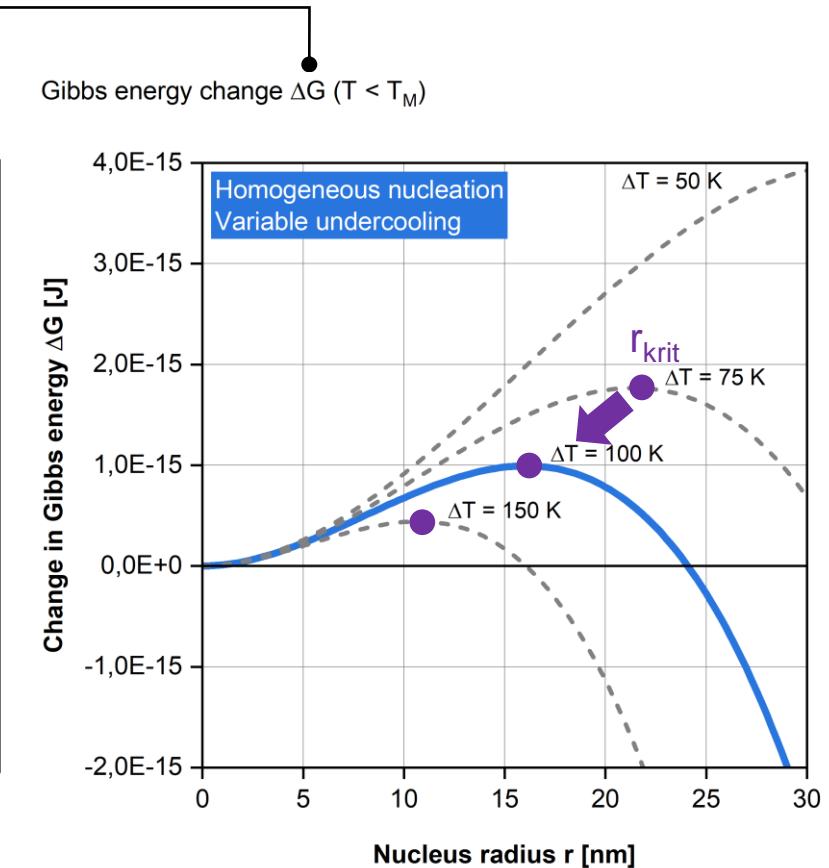
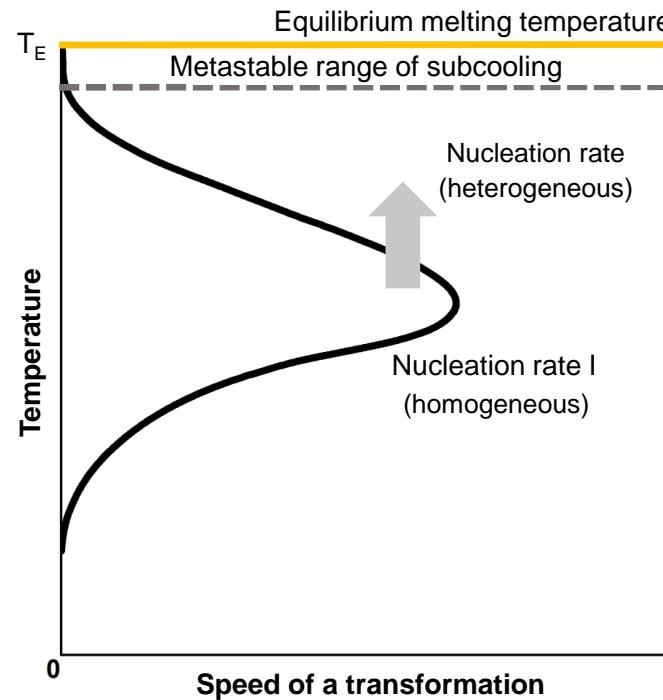


Speed of transformations

Heterogeneous nucleation

- Please note: ΔG_k is not a constant but depends on the temperature

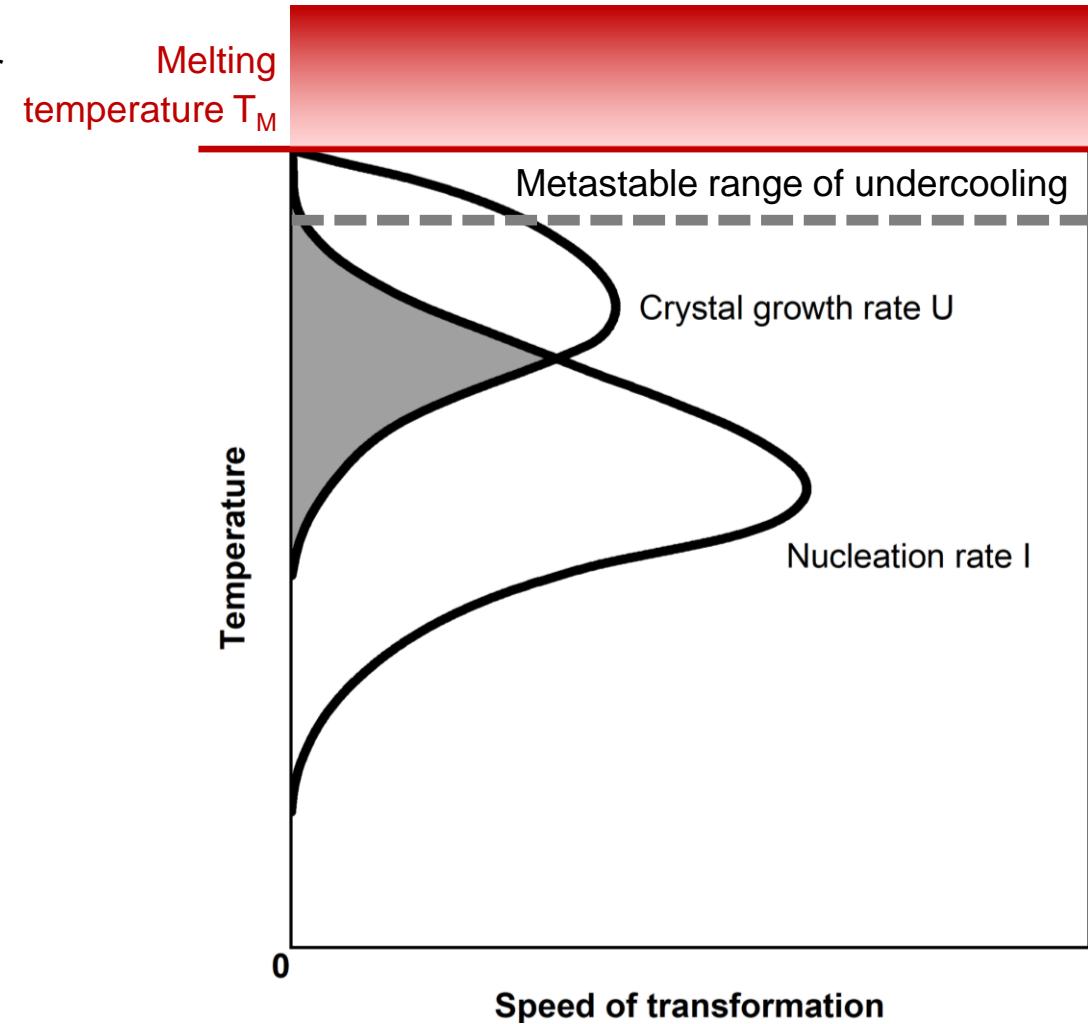
- Similar process in **heterogeneous nucleation**; however, the crystallization nucleus is formed on a **solid surface**, e.g., on a mold wall or an impurity particle in the melt
- Heterogeneous nucleation takes place on favorable surfaces, i.e., those with low interfacial energy to the crystal nucleus → the **energetic disadvantage** for the formation of the new interface **decreases**
- The barrier ΔG for heterogeneous nucleation is therefore significantly lower → peak value of the nucleation rate shifts closer to the melting point



Speed of transformations

Transformation rates

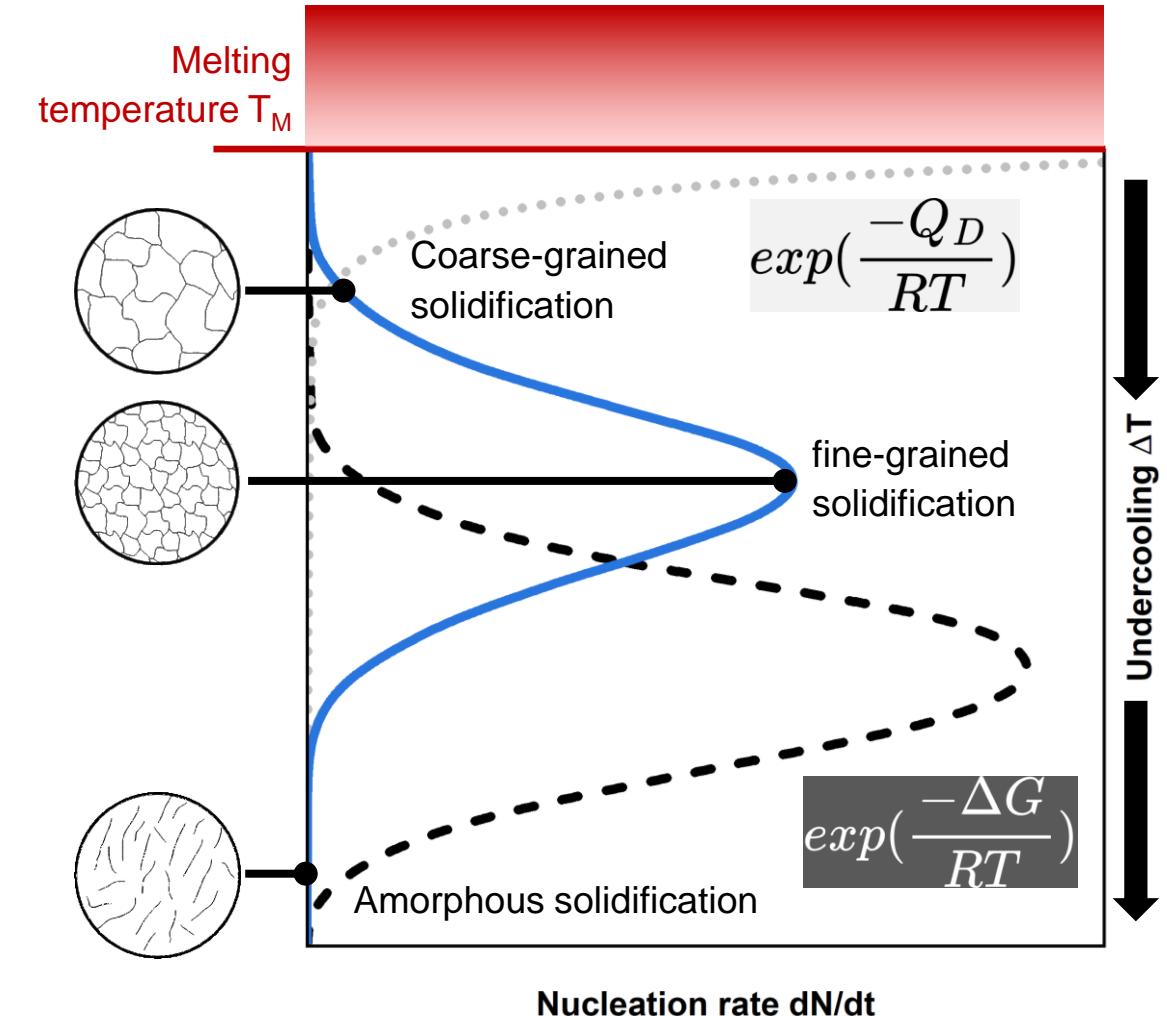
- Nucleation is followed by **crystal growth**: process of adding atoms or molecules to a crystal
- Specification of the **crystal growth rate** U as (linear) speed at the interface between crystal and melt
- Structure and chemistry of the crystallizing material define the properties of the growth processes (\rightarrow **microstructural properties**, **microstructural morphology**)
- Crystal growth rate generally follows the schematic diagram shown: velocity increases steeply when the temperature drops below T_M , reflecting the thermodynamic driving force for the phase change
- The decreasing growth is due to slower diffusion at lower temperatures



Speed of transformations

Effects on the resulting microstructure

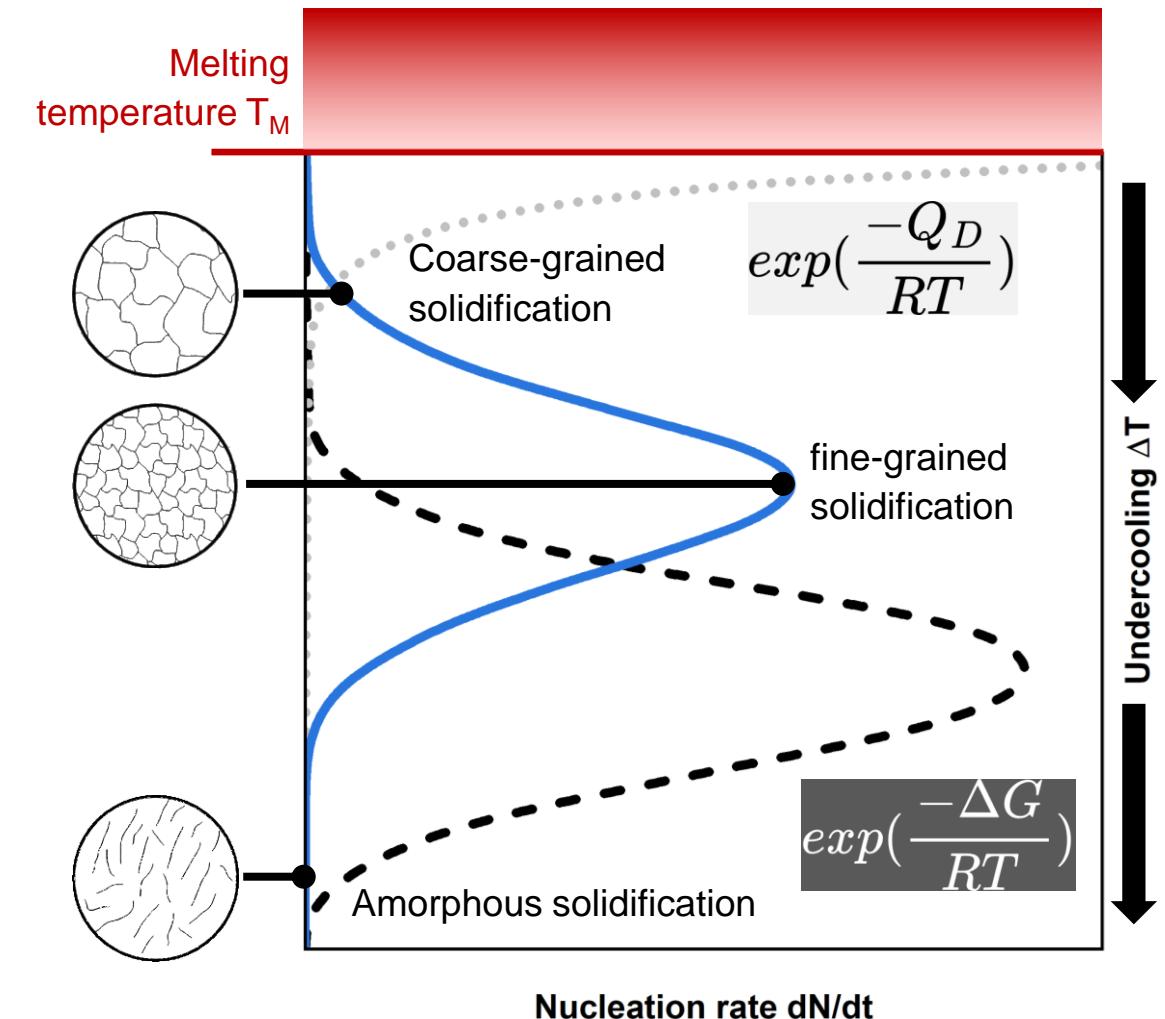
- **Low undercooling:** Nucleation work $\Delta G_k \gg$ Activation work Q_D of diffusion
- Inhibition of nucleation due to the high nucleation energy required



Speed of transformations

Effects on the resulting microstructure

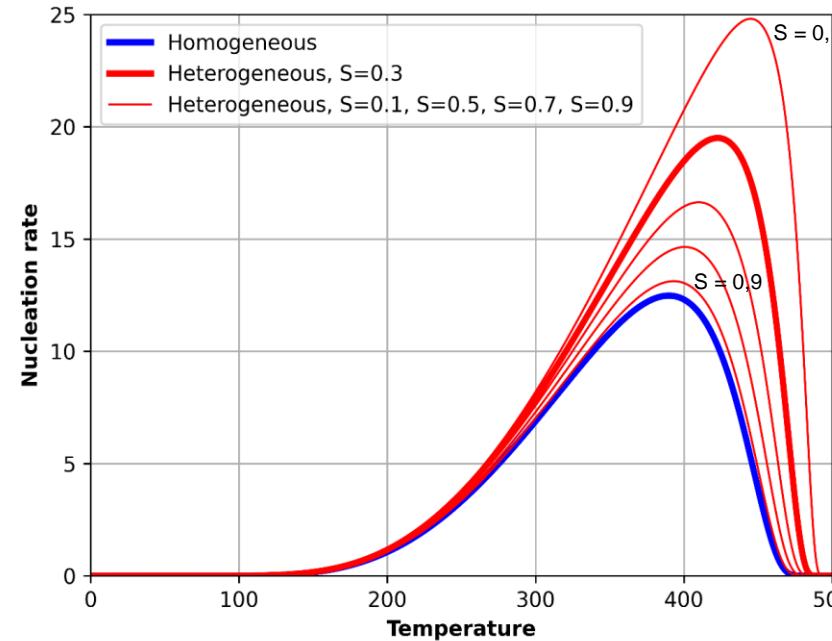
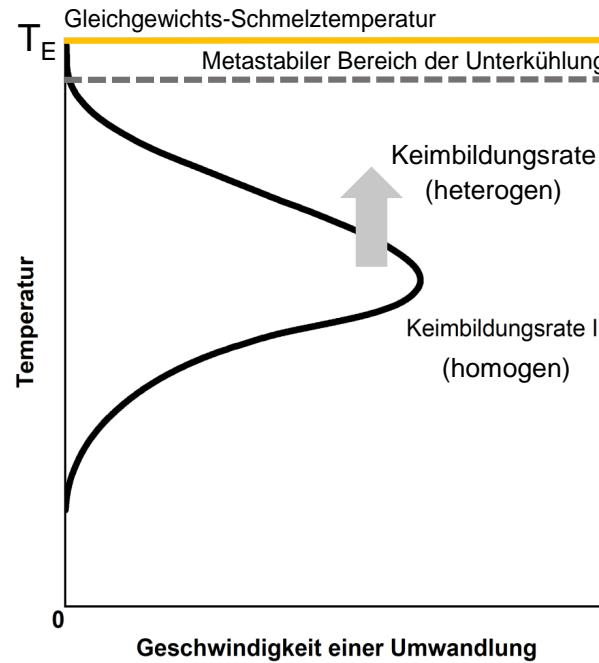
- **High undercooling:** inverse process: Activation energy Q_D of diffusion $>>$ nucleation energy $\Delta G_k \rightarrow$ inhibits the formation of a nucleus
- With increasing undercooling, not enough particles come together to form a nucleus and cause it to grow
- Less diffusion:
 - in the **melt**,
 - across the **phase boundaries**,
 - within the **nucleus**
- Excessive undercooling can completely suppress nucleation \rightarrow solidification of the undercooled melt without crystallization
- Particles are "frozen" before they could have combined to form a crystal structure \rightarrow **amorphous materials** (e.g., metallic glasses)



Speed of transformations

Heterogeneous nucleation

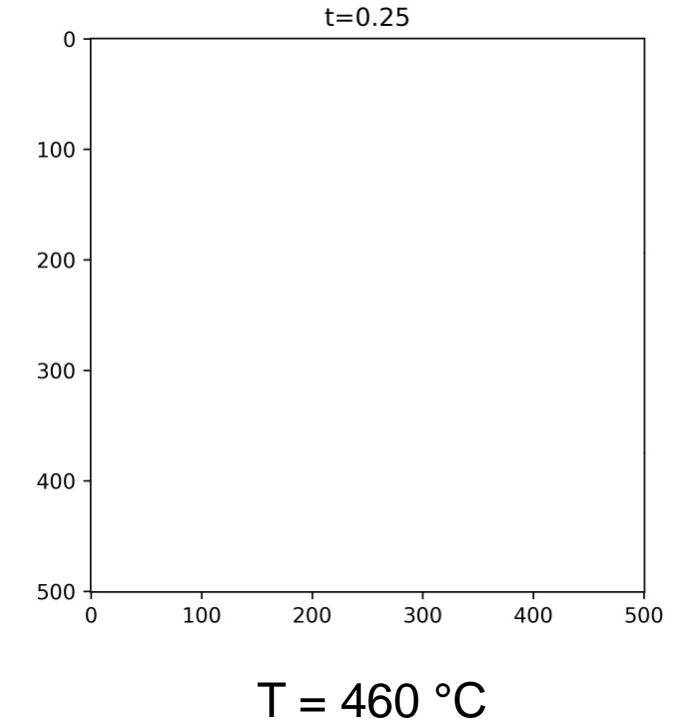
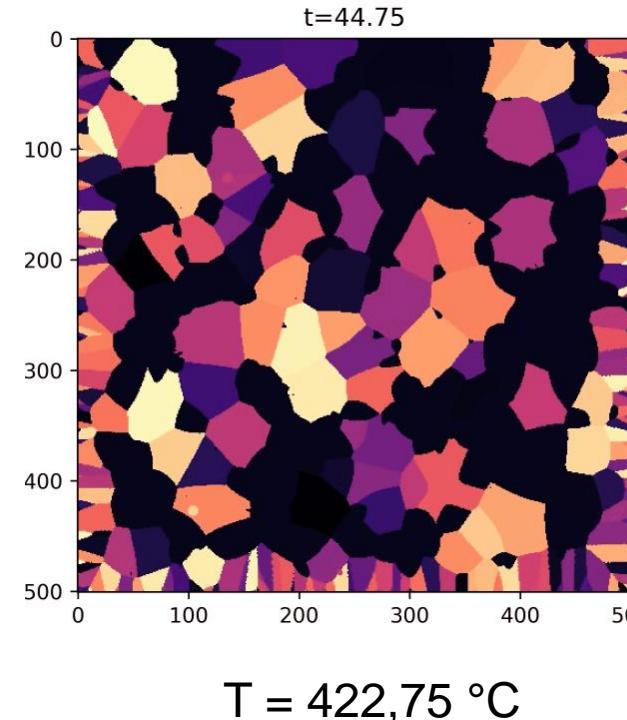
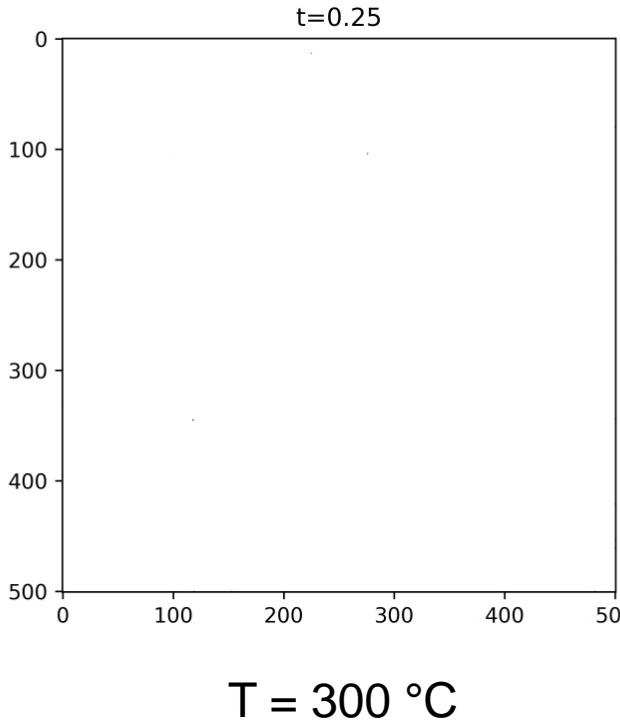
- Consequently, a **maximum nucleation rate** at a defined undercooling, high probability of nucleation → fine-grained microstructure
- **Sufficiently high undercooling** is therefore **generally desirable**, as this leads to a fine-grained microstructure → good strength properties of the microstructure
- **Heterogeneous nucleation** also has a positive influence on the **nucleation rate**:



Speed of transformations

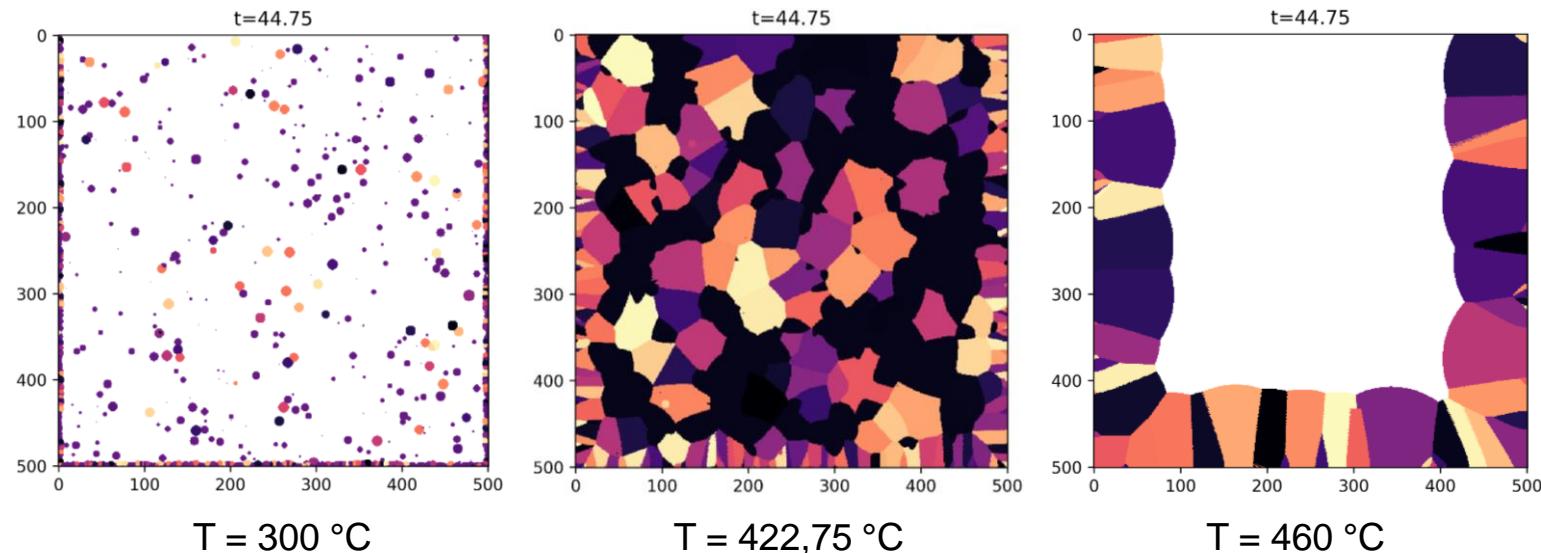
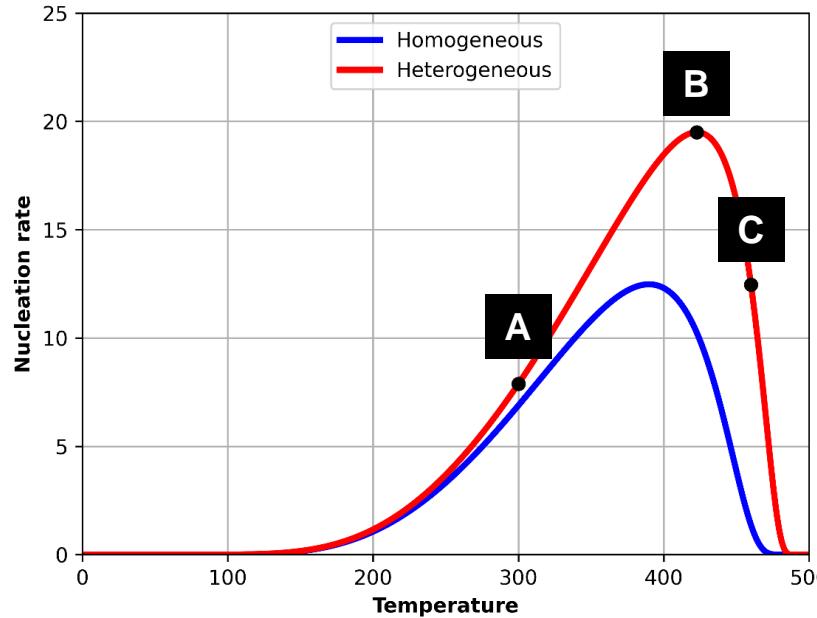
Comparison of different undercoolings

- Assumed **homogeneous temperature distribution** → uniform undercooling; preferred nucleation at the boundary due to the surrounding mold (higher probability of nucleation due to wetting on the mold wall)



Speed of transformations

Comparison of different undercoolings

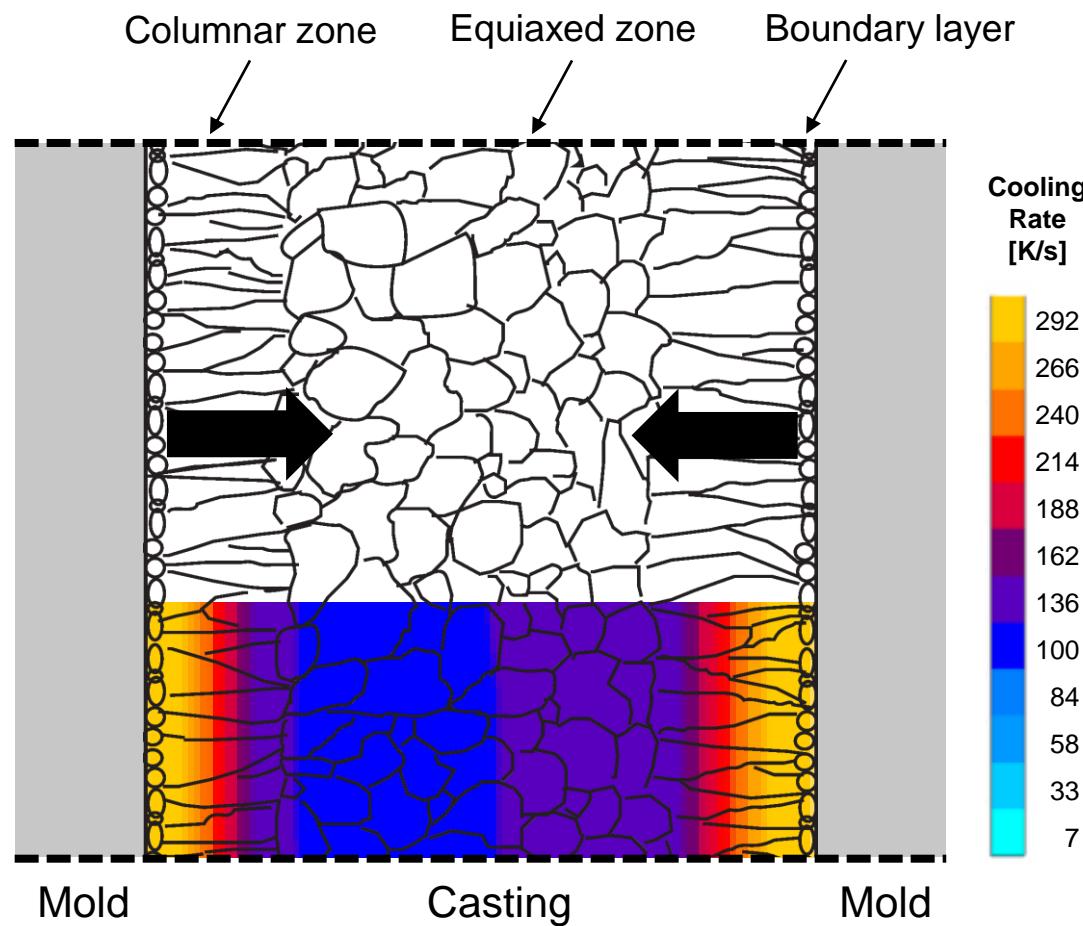


- A** **High undercooling:** high probability of nucleation, low crystal growth rate due to limited diffusion → high number of small crystals, no complete solidification for a given time interval
- B** **Moderate undercooling:** lower probability of nucleation, higher crystal growth rate due to increased diffusion → smaller number of crystals but faster crystal growth → full solidification for a given time interval
- C** **Limited undercooling:** low probability of nucleation, high crystal growth rate – cannot compensate low probability of nucleation however → no complete solidification for a given time interval

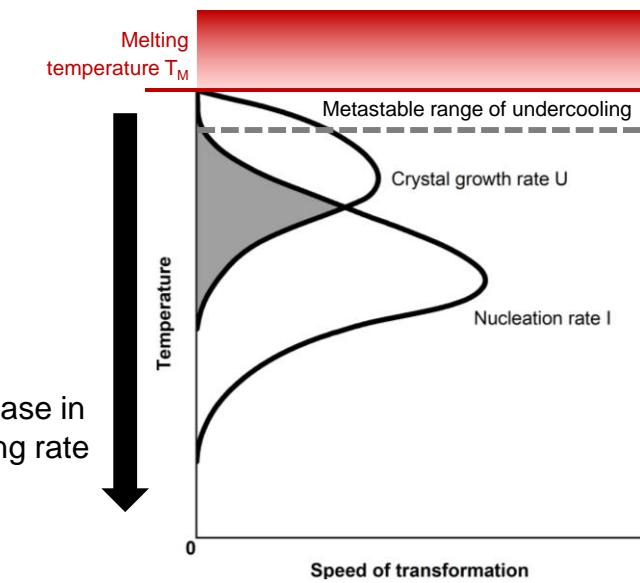
Chapter 1.4: Solidification morphologies in metals

Solidification morphologies in metals

Introduction

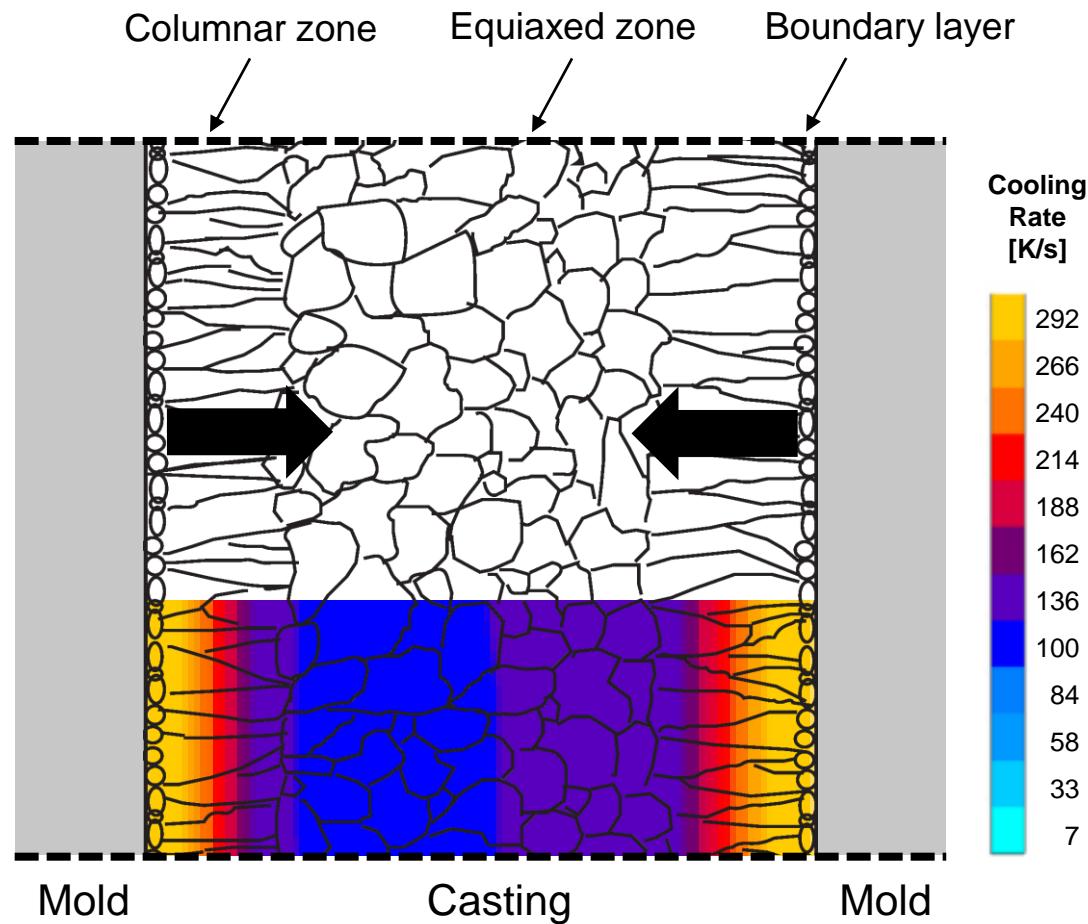


- Schematic of the grain structures that form during the solidification of a metal within a mold
- These grain structures arise due to the different **cooling rates** and the **nature of crystal growth** during the casting process
- The cooling rates (as well as concentrations and surface tensions) therefore not only influence the nucleation and crystal formation rate, but obviously also the **morphology** (= shape) of the resulting microstructure



Solidification morphologies in metals

Introduction



Boundary Layer

- Typically, only the metal touching the mold's surface cools below its equilibrium freezing temperature, forming a fine-grained structure as numerous crystals emerge and solidify swiftly

The key question is how solidification progresses into the melt – this requires **heat removal through the solid layer**, lowering the freezing front's temperature below equilibrium:

Columnar Zone

- Further away from the mold wall, a slower cooling rate enables the development of elongated, columnar grains that grow perpendicular to the mold due to the steeper temperature gradient

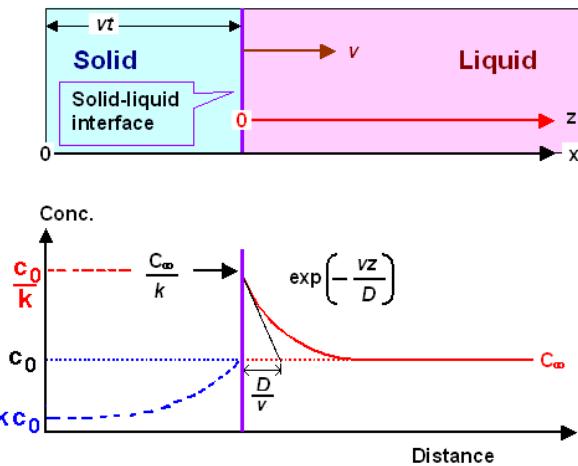
Equiaxed Zone

- Central to the casting, the slowest cooling occurs, enabling uniform grain growth in all directions, producing isotropic, equiaxed grains due to a gentler temperature gradient

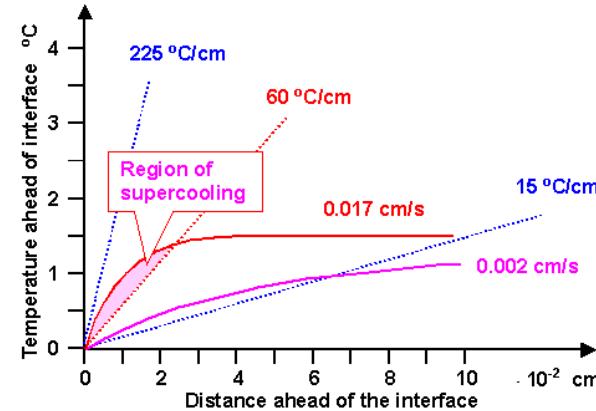
Solidification morphologies in metals

Consideration of concentration differences – Constitutional undercooling

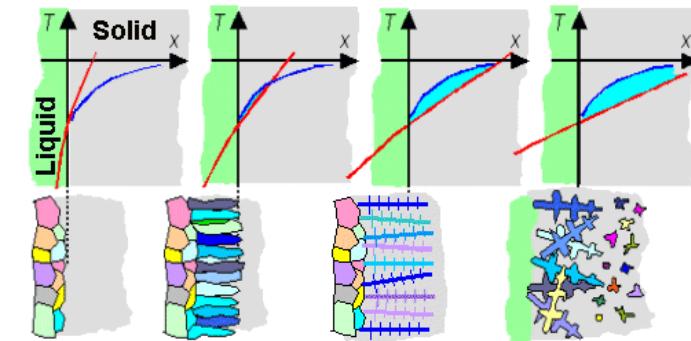
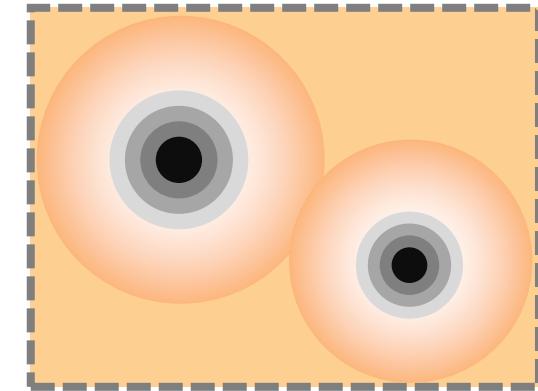
- The assumption of complete mixing in the melt cannot be maintained, as there is usually **no sufficiently high convection of the melt** to reduce the resulting concentration gradients
- **Concentration gradients** occur in the immediate vicinity of the nuclei or the growing grains



Actual temperature rise (dashed lines) and melting point change (solid lines) in front of the solid-liquid interface



Source: H. Föll (Iron, Steel and Swords script) | Segregation Science | Christian-Albrechts-Universität zu Kiel



Schematic representation of the solidification morphology at different degrees of supercooling

Solidification morphologies in metals

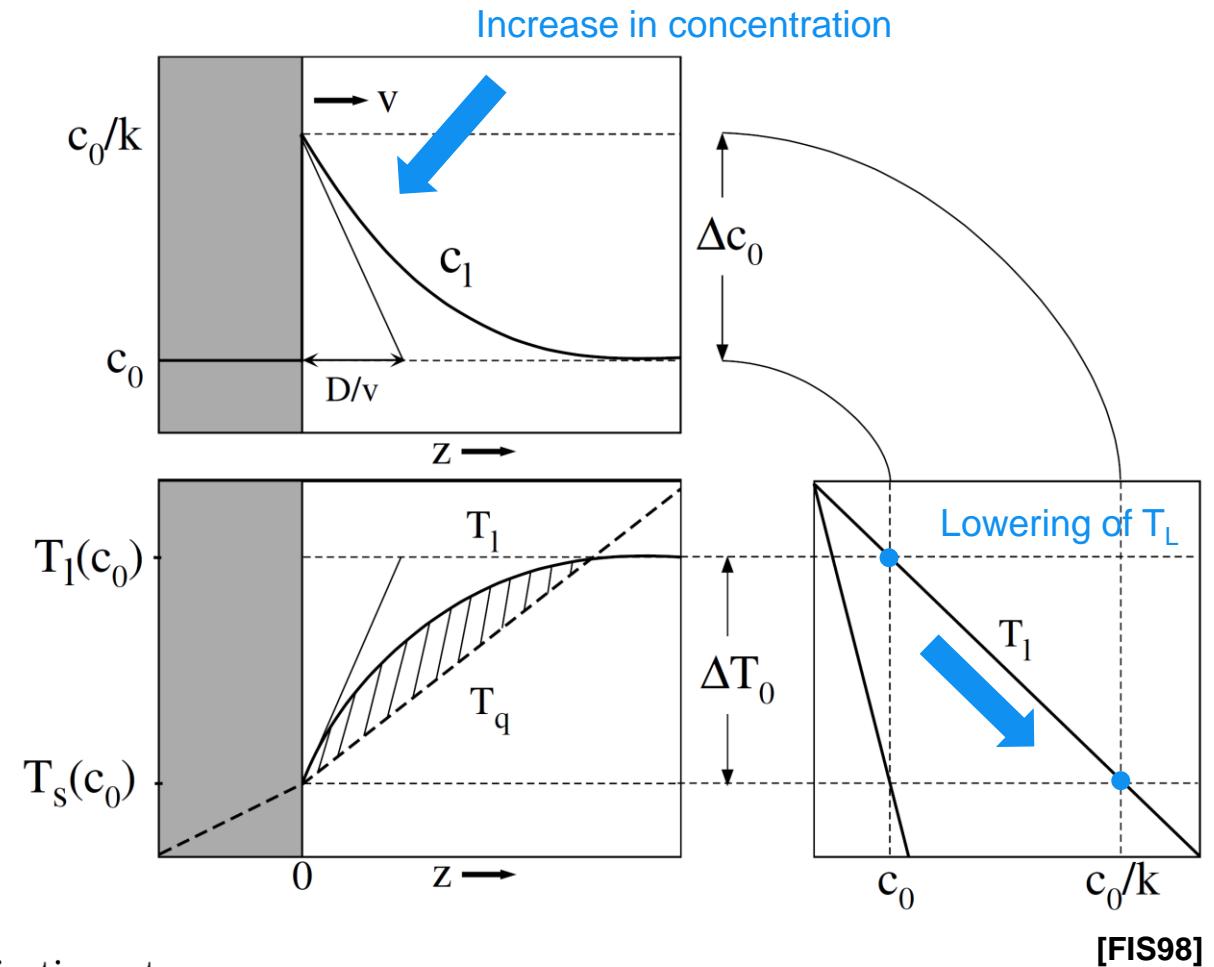
Constitutional undercooling

- **Different solubilities** of the individual alloying elements of an alloy
- The components that are less soluble in the solid phase are **rejected** at the liquid/solid phase boundary and **diffuse back** into the melt
- **In the melt:** Accumulation of the components that are less soluble in the solid in front of the phase boundary (**micro-segregation**):
 - **Increase in the concentration**
 - Lowering of the local equilibrium liquidus temperature
 - Temperature falls locally below the liquidus temperature despite an increasing temperature gradient
- At the solidification front: concentration increase by ΔC_0 of the dissolved component to C_0/k
- Exponential drop in concentration in the melt to $C_L = C_0$

$$C_L = \Delta C_0 \exp\left(-\frac{v}{D_L} z\right) \quad \text{Eq. 1.4.1}$$

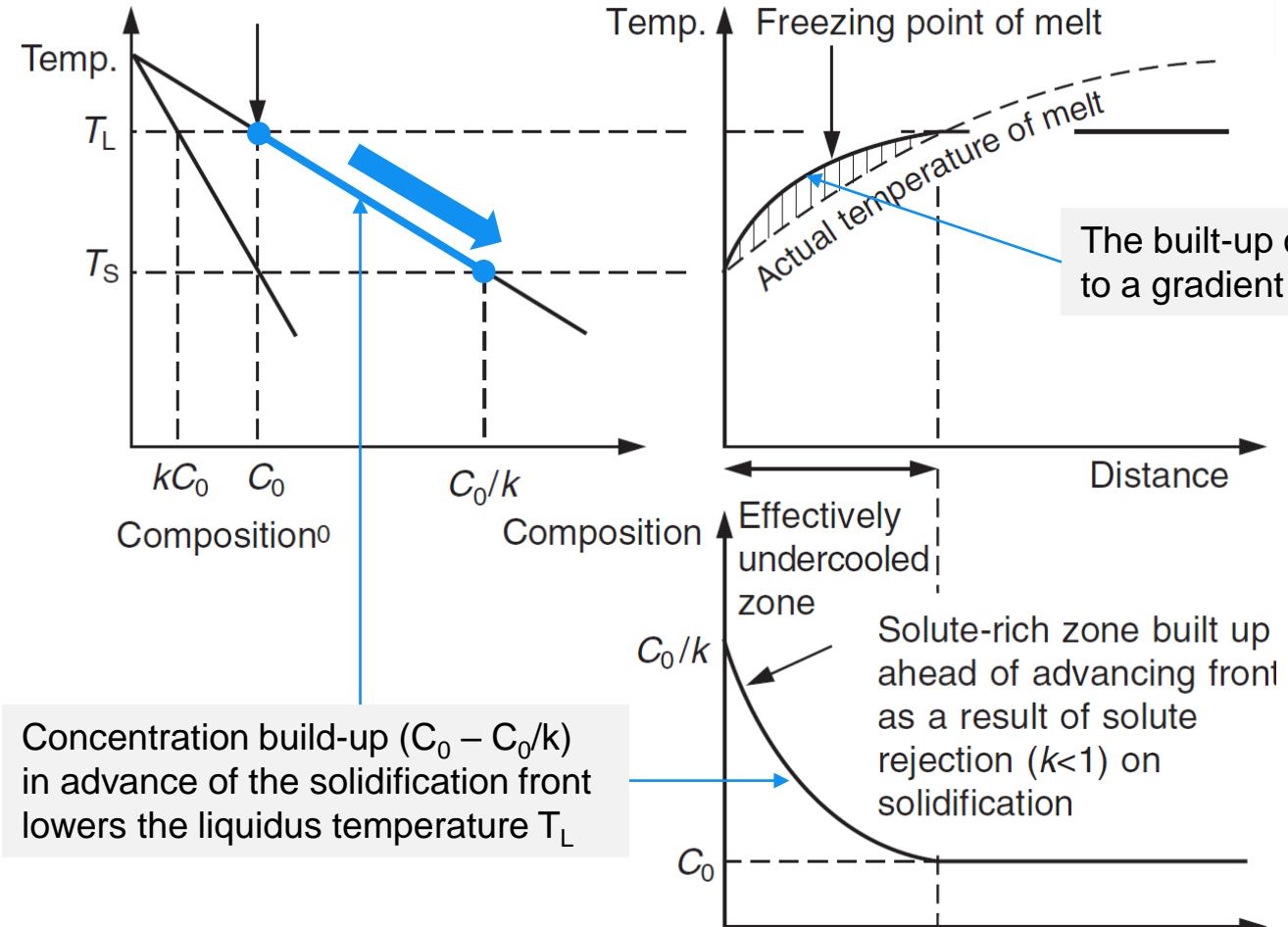
v Solidification rate

D_L Diffusion coefficient (liquid)



Solidification morphologies in metals

Constitutional undercooling



Solidification morphologies in metals

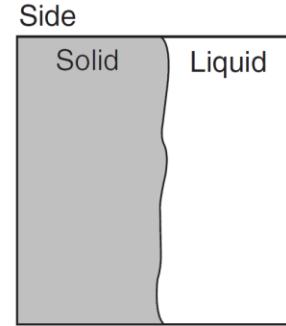
Constitutional undercooling – Different solidification morphologies

A

Plane growth

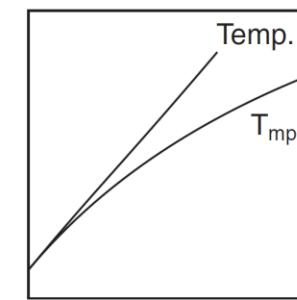


Front



Side

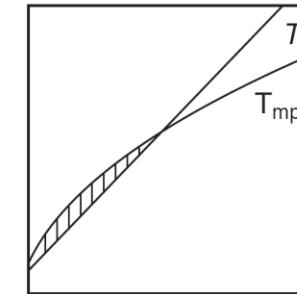
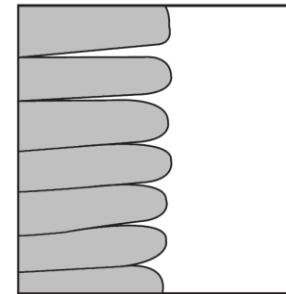
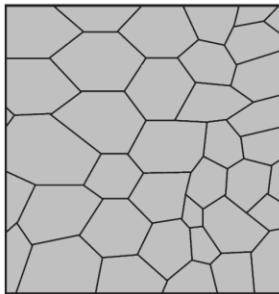
Temperature regime



- Three different **solidification morphologies** in metals and their associated temperature gradients during the solidification process due to effective **undercooling** from segregation of alloying elements, lowering the liquid's melting
- Transition of growth morphology from **planar**, to **cellular**, to **dendritic**, as constitutional undercooling increases

B

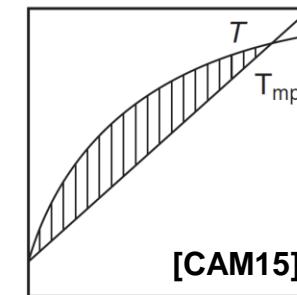
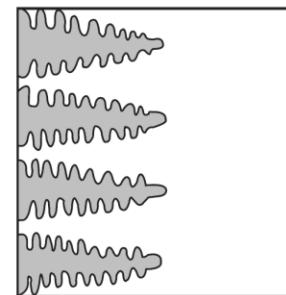
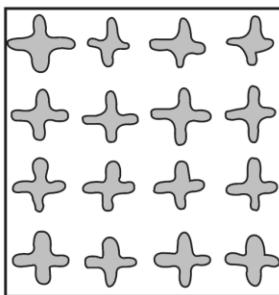
Cell growth



- Morphologies influence the mechanical properties of the metal
- Plane growth typically leads to fewer defects and can result in a stronger, more ductile metal
- Cell and dendrite growth can lead to segregation of alloying elements and porosity, which can weaken the metal

C

Dendrite growth



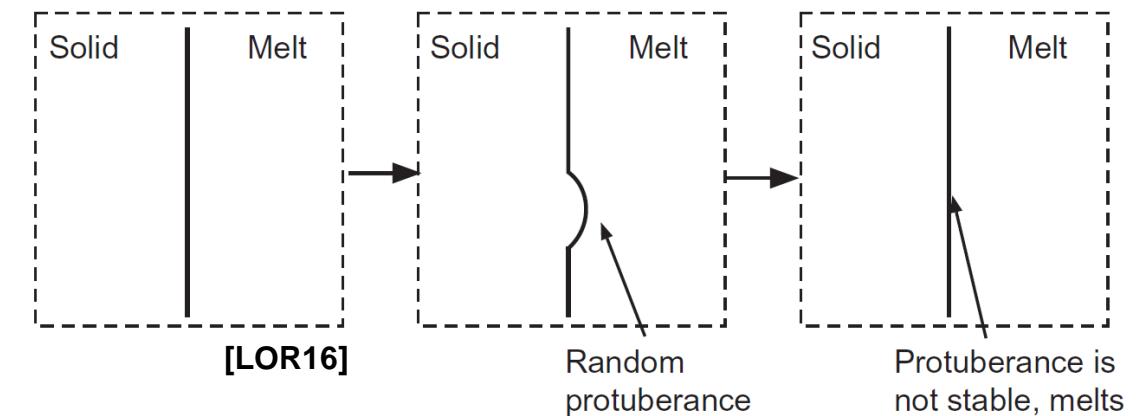
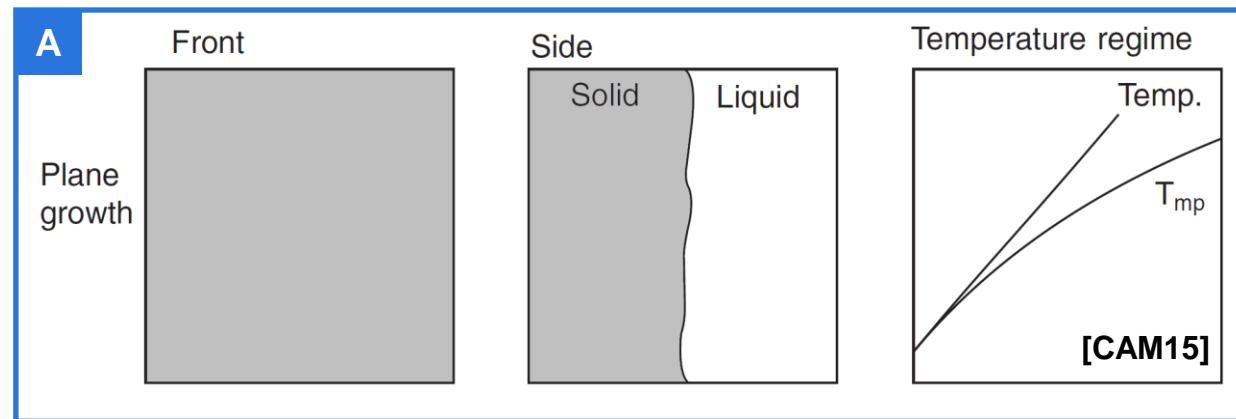
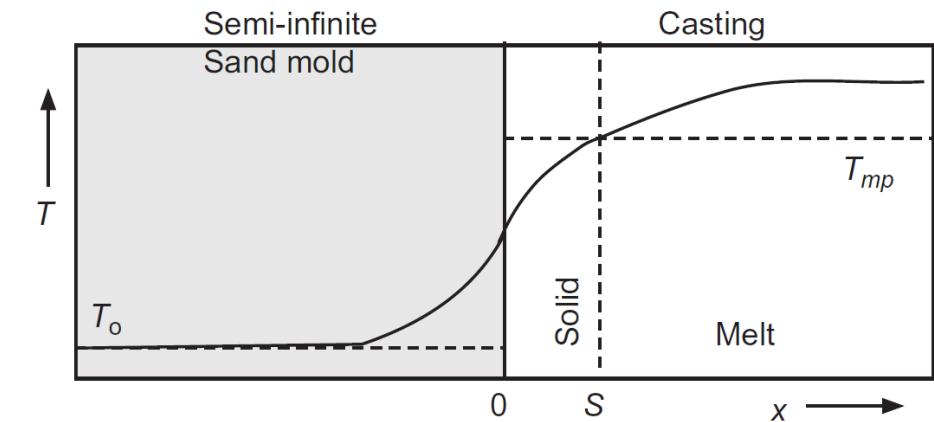
[CAM15]

Solidification morphologies in metals

Constitutional undercooling – Different solidification morphologies

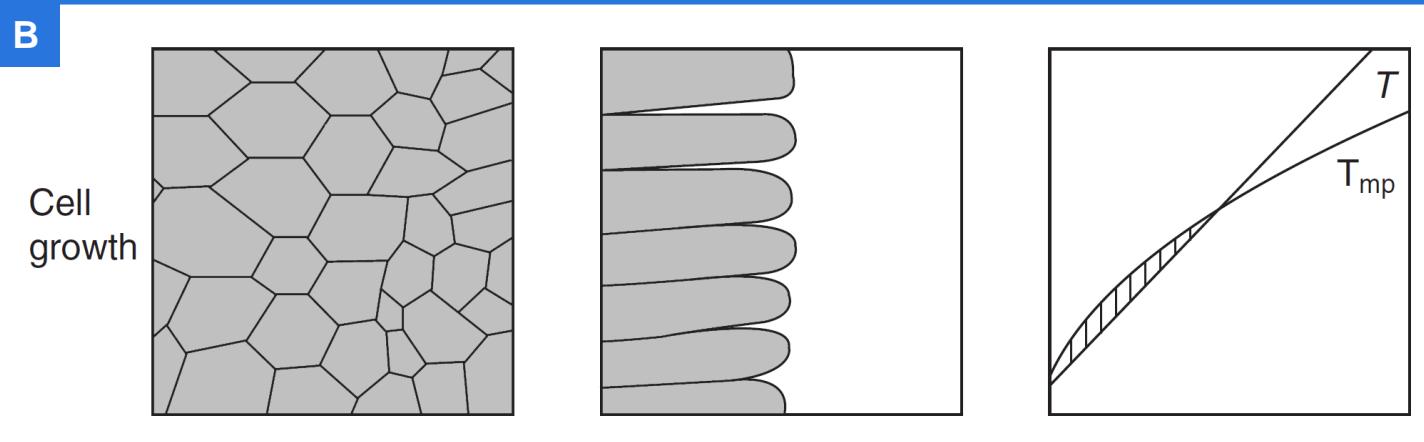
Plane Growth:

- Simplest form of solidification, where the solid/liquid interface is flat; temperature in the solid is uniform and just below the melting point (T_{mp})
- Mold is at a lower temperature than the melt \rightarrow nucleation occurs preferentially at the **mold surface**
- As heat is extracted into the mold, the metal cools progressively away from the mold surface \rightarrow solidification front advances uniformly into the liquid



Solidification morphologies in metals

Constitutional undercooling – Different solidification morphologies

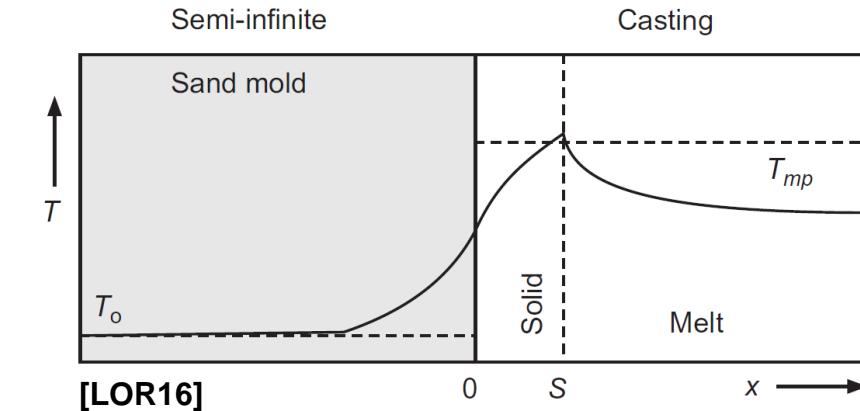
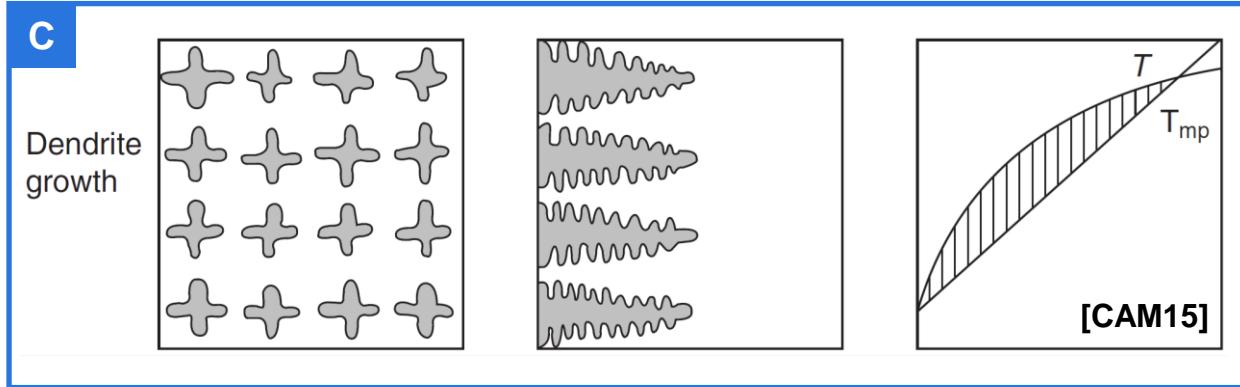


Cell Growth:

- As the cooling rate increases or the composition changes, the solid/liquid interface becomes unstable, leading to the formation of cells
- Cells are polygonal at the front view and elongated at the side view
- Temperature gradient at the interface indicates that the solid is slightly below the melting point at the cell boundaries and closer to the melting point within the cells

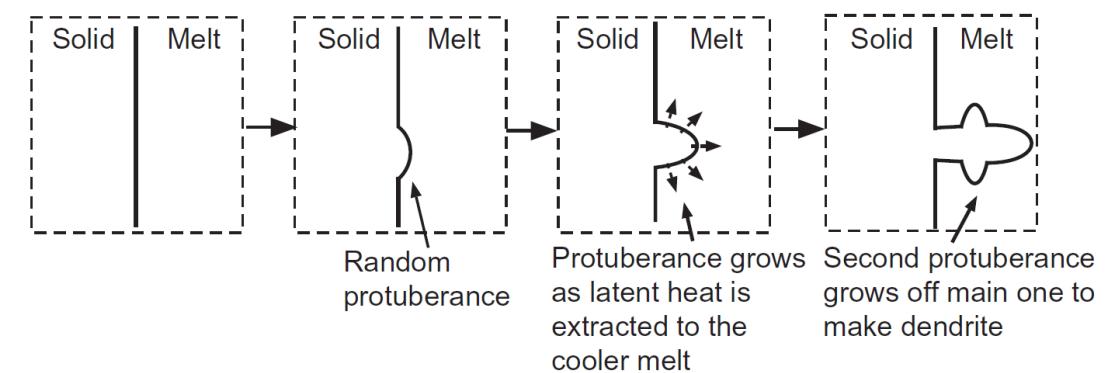
Solidification morphologies in metals

Constitutional undercooling – Different solidification morphologies



Dendrite Growth:

- Existing non-uniform distribution of solute during solidification (**concentration difference**), leading to a **constitutional undercooling ahead of the solid/liquid interface**
- The temperature gradient is steeper, with a **larger undercooled region** in the liquid ahead of the interface, which promotes dendritic growth (accelerating the solid's advance)
- At even higher cooling rates or under certain alloy conditions, the cells become unstable and branch out, forming tree-like structures, called **dendrites** (Greek 'Dendros' for tree)



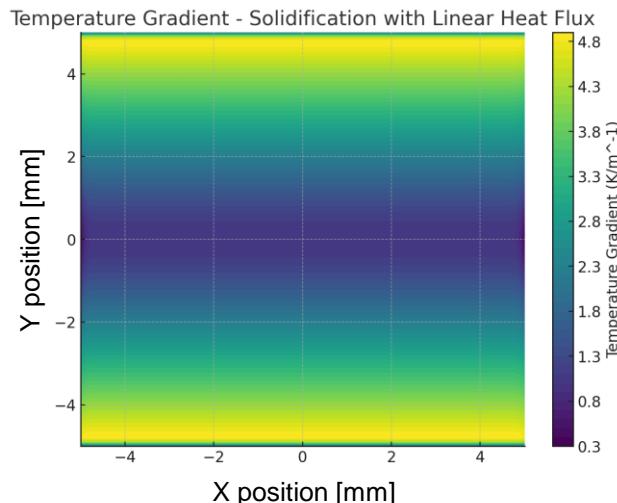
Solidification morphologies in metals

G/V – diagram

- Crucial in materials engineering for predicting the grain structure of a material as it solidifies, which has a significant impact on its mechanical properties
- Understanding and controlling the variables represented in this diagram allows engineers to **tailor materials and process** for specific applications by controlling the microstructure

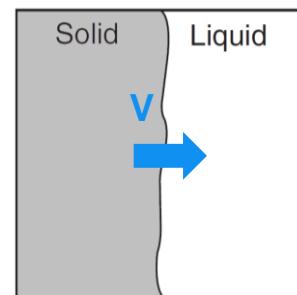
Temperature gradient (G)

Represents the rate at which temperature changes with distance within the material



Isothermal velocity (V)

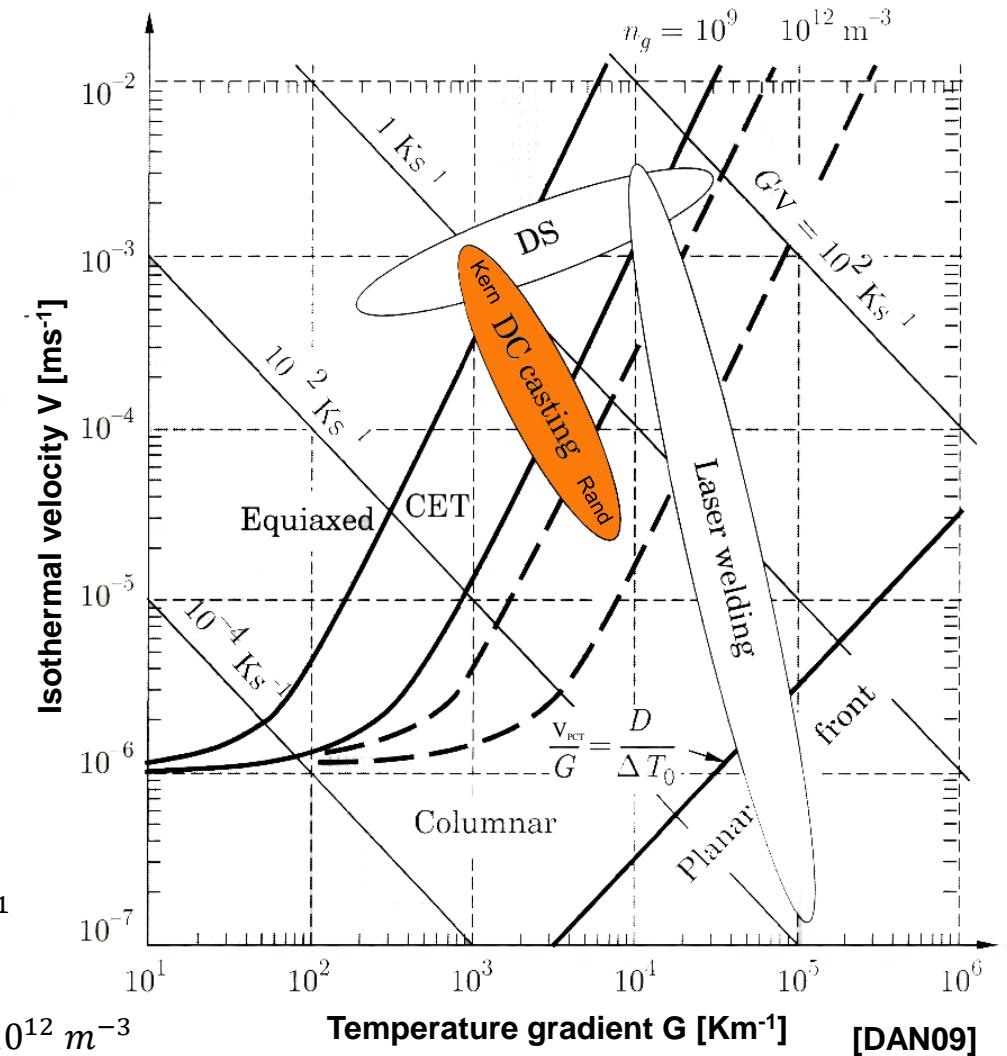
Velocity at which the isotherm moves during solidification



$$D = 3 \cdot 10^{-9} m^2 s^{-1}$$

$$\Delta T_0 = 100 K$$

$$n_g = N_0 = 10^9 \dots 10^{12} m^{-3}$$



Solidification morphologies in metals

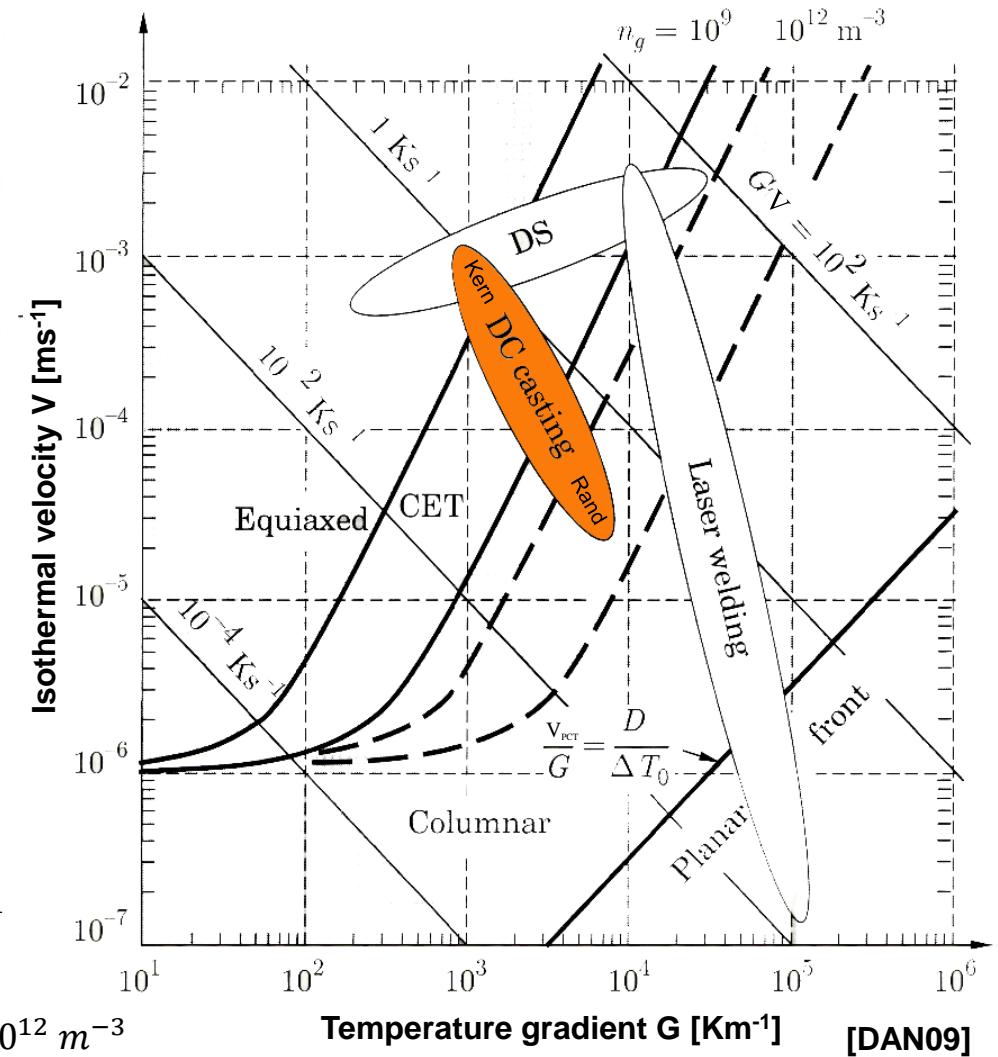
G/V – diagram

- G/V – diagram to **describe specific manufacturing processes** like direct chill (DC) casting and laser welding operate within certain regions of the G/V diagram, indicating the conditions under which these processes occur
- **Stable and Unstable Regions:** Regions of stability and instability for the growth of solid phases; stability can refer to steady-state growth of the solid, while instability can lead to various forms of microstructural defects or patterns.
- **Solidification Modes:** Various zones or curves in the diagram represent different modes of solidification, such as:
 - **Equiaxed Zone, Columnar Zone: Planar Front Solidification (PCT)**
- **Lines of Constant Solidification Time** indicate the time required for the solidification front to pass, and they help in understanding the kinetics of the solidification process
- **Nucleation Rates** indicating the nucleation rate of new grains, with higher rates typically associated with equiaxed structures

$$D = 3 \cdot 10^{-9} \text{ m}^2 \text{s}^{-1}$$

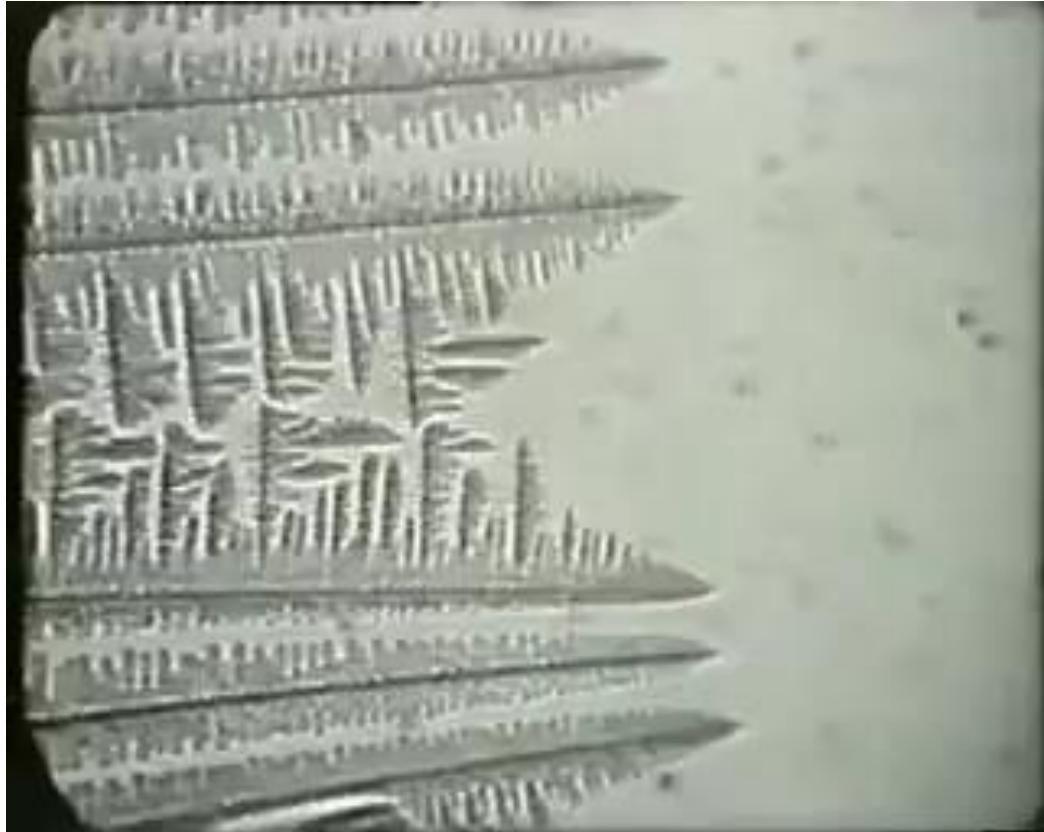
$$\Delta T_0 = 100 \text{ K}$$

$$n_g = N_0 = 10^9 \dots 10^{12} \text{ m}^{-3}$$



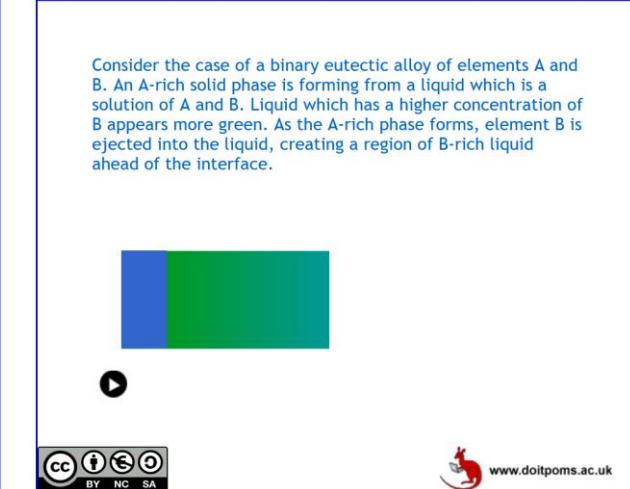
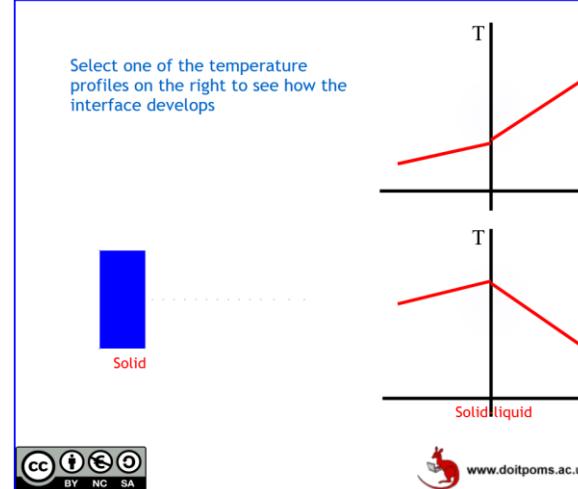
Solidification morphologies in metals

Visualisation of dendritic growth



Competing growth of dendrite structures

Source: Wilfried Kurz, Swiss Federal Institute of Technology Lausanne, Switzerland



Further reading from



UNIVERSITY OF
CAMBRIDGE

Dissemination of IT for the Promotion of Materials Science (DoITPoMS)

Dendritic Growth:

https://www.doltpoms.ac.uk/tplib/solidification_alloys/dendritic.php

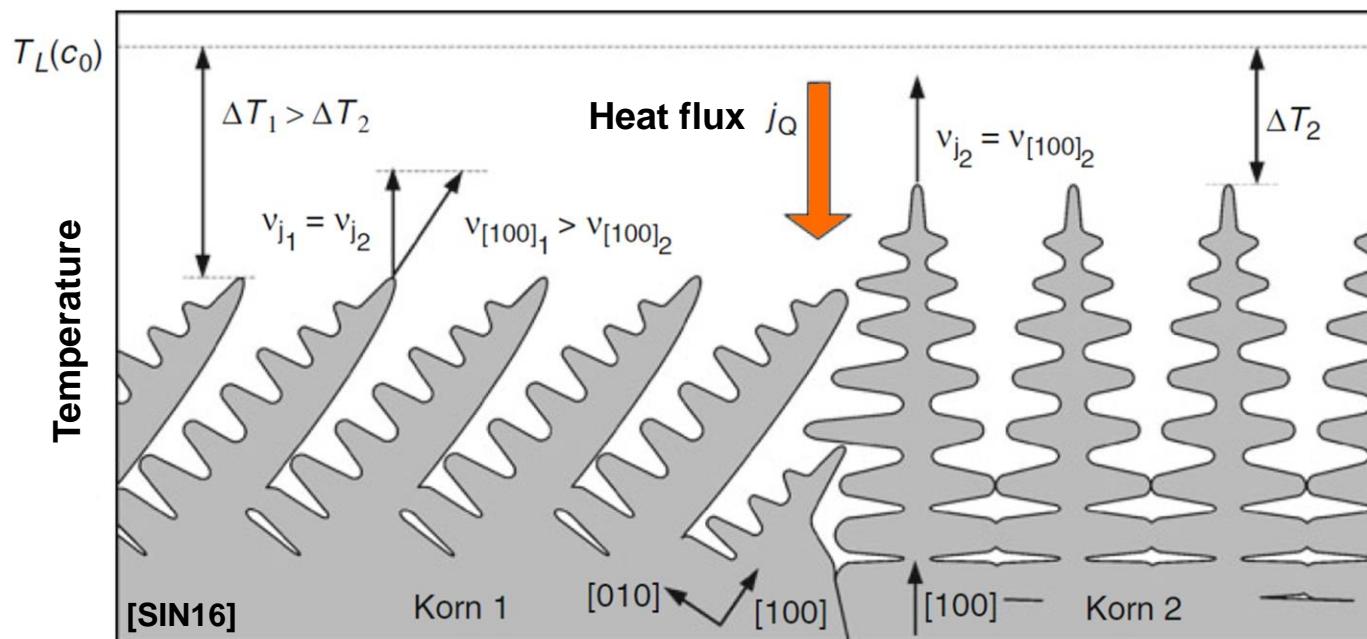
Constitutional Undercooling:

https://www.doltpoms.ac.uk/tplib/solidification_alloys/undercooling.php

Solidification morphologies in metals

Competition in crystal growth

- Different growth rates of grains in different spatial directions due to the stochastic orientation of the nuclei from which they originated
- Grains always grow first along their main axes, as this causes the smallest surface enlargement
- The solidification front always moves in the direction of the highest temperature gradient
- The grains whose main axes point in the direction of the temperature gradient overgrow the grains with a less favorable orientation



Growth of dendrites in response to an instability condition in the environment ahead of the growing solid, not the result of some influence of the underlying crystal lattice

Chapter 1.5: Melt rheology

Outline

Process step: Mold filling

The **flow behavior of the melt** determines how it fills the mold: a proper understanding of the melt's rheology can help in predicting and controlling the mold filling process; this is essential to ensure complete filling of the mold

Influenced by

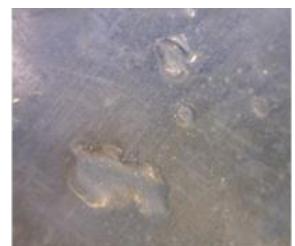
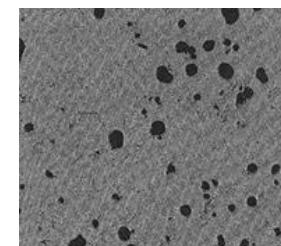
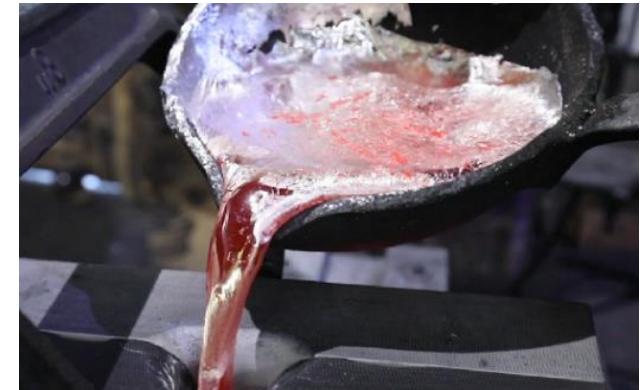
- Wetting behavior:** The melt's interaction with the mold walls (wetting behavior) can affect the quality of the final product; good wetting ensures a smooth surface finish and reduces defects
- Solidification:** As the melt cools and solidifies, its rheological properties change; understanding this transition helps in controlling the solidification rate and ensuring a uniform microstructure in the final product

Aim: Defects avoidance

Many casting defects, such as air entrapment, cold shuts, and weld lines, are influenced by the flow behavior of the melt; by understanding and controlling the rheology, these defects can be minimized

Fields of action in casting technology: Finding optimal process ranges

Knowledge of melt rheology helps in setting optimal processing parameters like injection speed, pressure, and temperature, ensuring efficient and defect-free casting



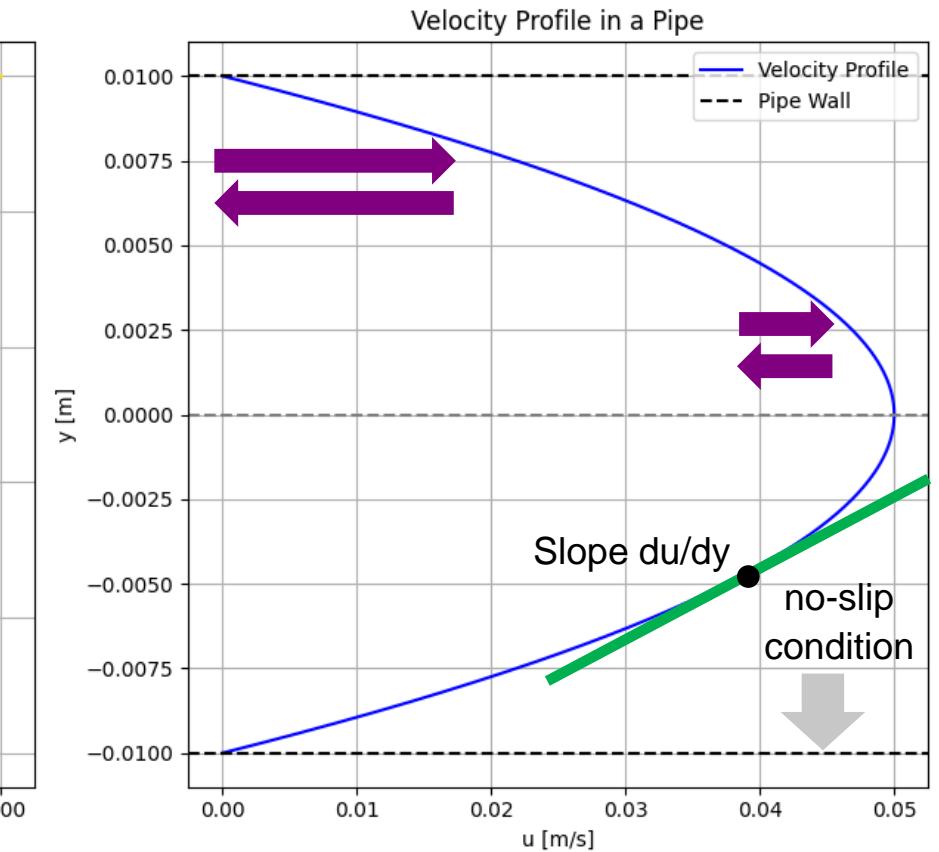
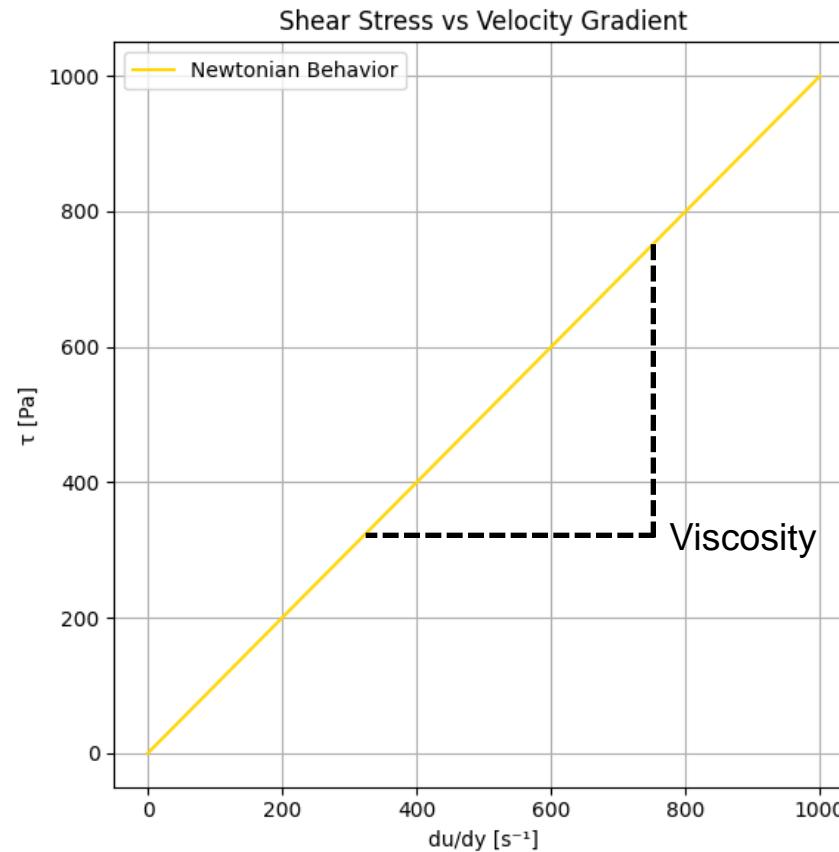
- **Viscosity:** One of the primary properties studied in melt rheology is viscosity, which is a measure of a fluid's resistance to shear or flow
- The viscosity of molten materials can change with **temperature, shear rate and time**

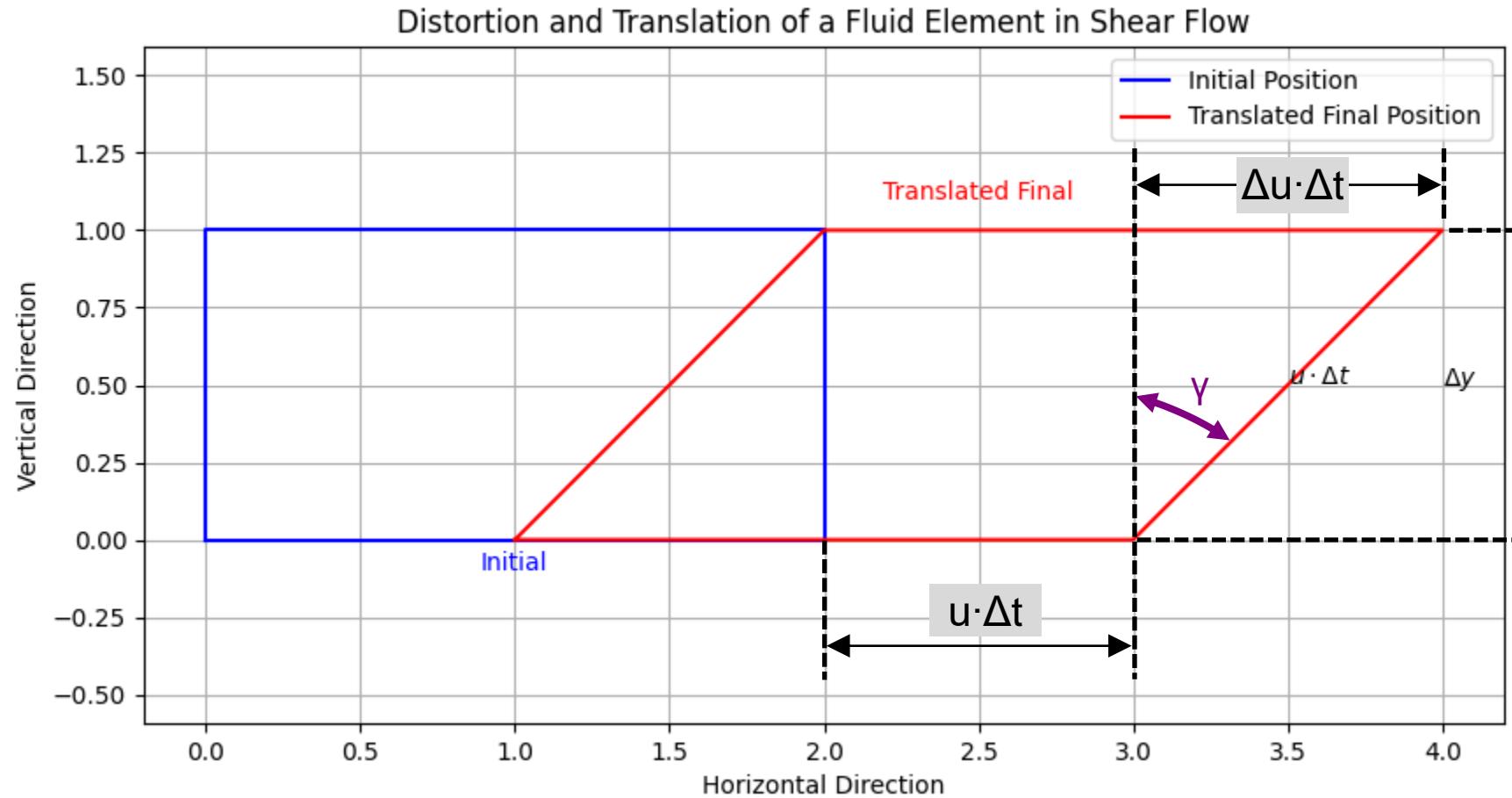
Newton's Law of Viscosity:

$$\tau = \eta \frac{du}{dy}$$

Eq. 1.5.1

- **Newtonian Fluids:**
Relationship between shear stress and velocity profile is linear
- Constant of proportionality:
Viscosity





Fluids

Shear strain rate
|
 $\tau = \eta \cdot \dot{\gamma}$ Eq. 1.5.4

Fluids respond by deforming continuously; they flow as long as the shear force is applied

Shear stress is a function of the rate at which strain changes over time

Solids

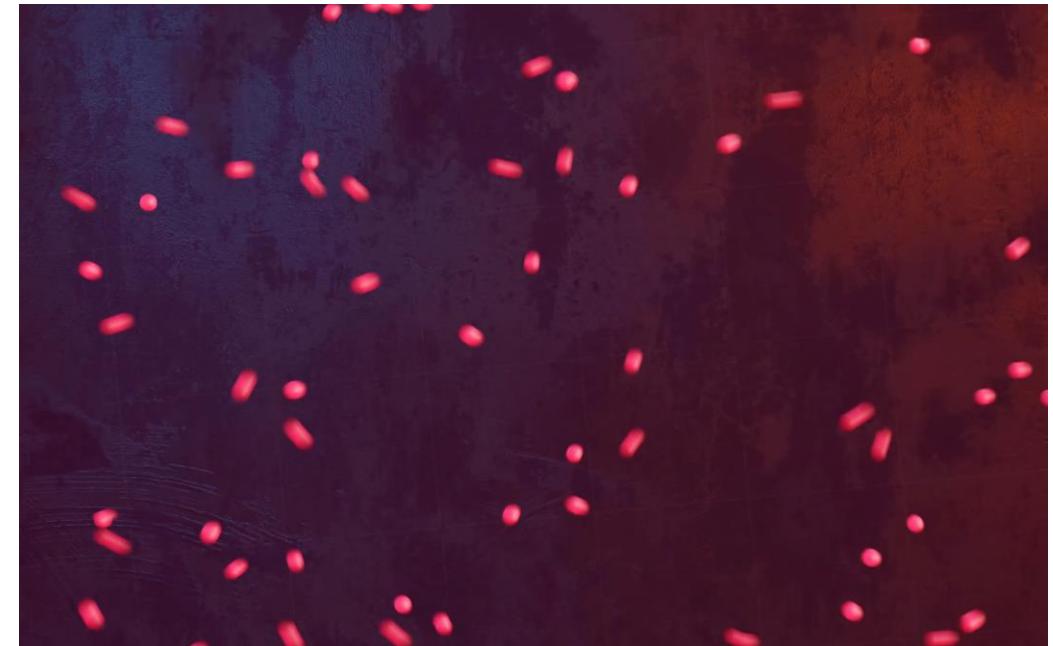
Shear strain
|
 $\tau = G \cdot \gamma$ Eq. 1.5.5

Solids respond to a constantly applied shear force with a finite amount of deformation

Deformation induced by a finite amount of deformation

Gases

- Molecules are widely spaced and move randomly at high speed
- Viscosity in gases is due to the transfer of momentum between fast-moving molecules when they collide with each other
- As gas molecules are farther apart, they have a **mean free path** (the average distance a molecule travels before colliding with another molecule), **which increases with temperature**
- **As temperature increases, gas viscosity increases** because the molecules move faster and collide more energetically, leading to greater momentum transfer



The efficient engineer, <https://youtu.be/VvDjhYSJv8>

Intermolecular collisions are
dominating the influence on viscosity

- **Viscosity of gases increase** with temperature due to more frequent and energetic molecular collisions
- **Sutherland's Law** provides a temperature-dependent model for gas viscosity:

$$\eta(T) = \eta_0 \left(\frac{T}{T_0} \right)^{\frac{3}{2}} \frac{T_0 + S}{T + S} \quad \text{Eq. 1.5.6}$$

where:

η_0 = Reference dynamic viscosity at temperature T_0 [Pa·s]

T = Temperature of interest [K]

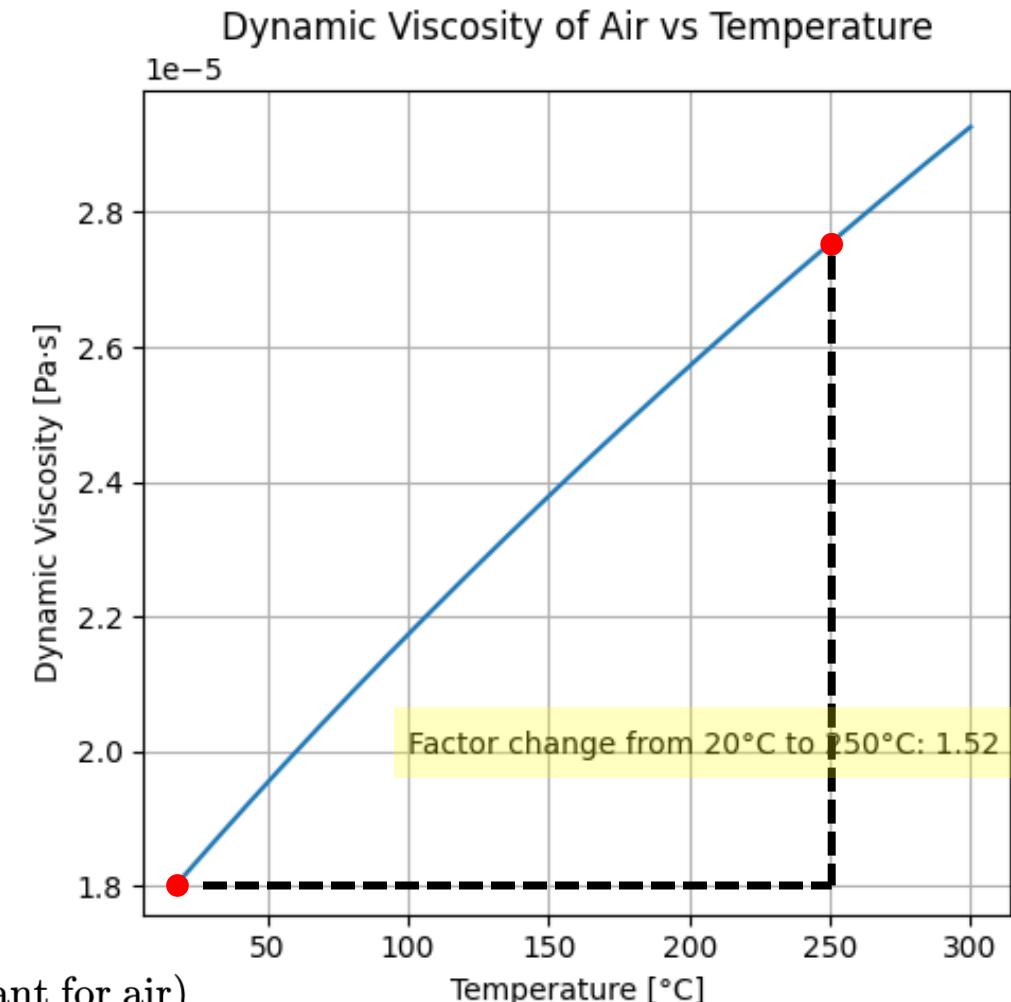
T_0 = Reference temperature [K]

S = Sutherland's constant [K]

$$\eta_0 = 1.716 \cdot 10^{-5} [\text{Pa} \cdot \text{s}]$$

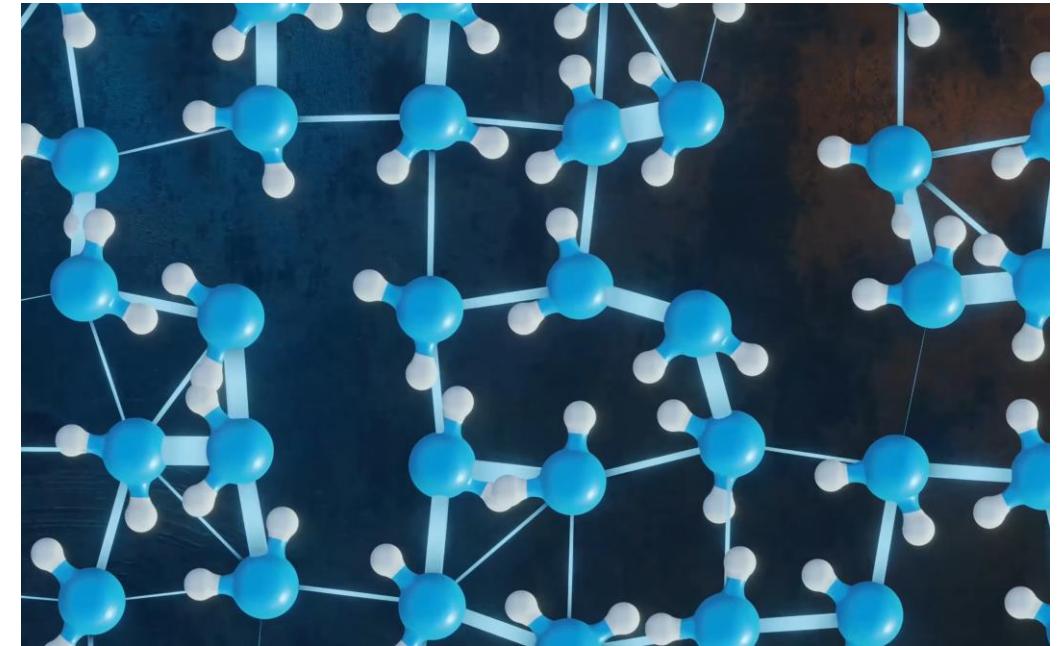
$$T_0 = 273.15 \text{ K}$$

$$S = 110.4 \text{ K} \text{ (Sutherland's constant for air)}$$



Fluids

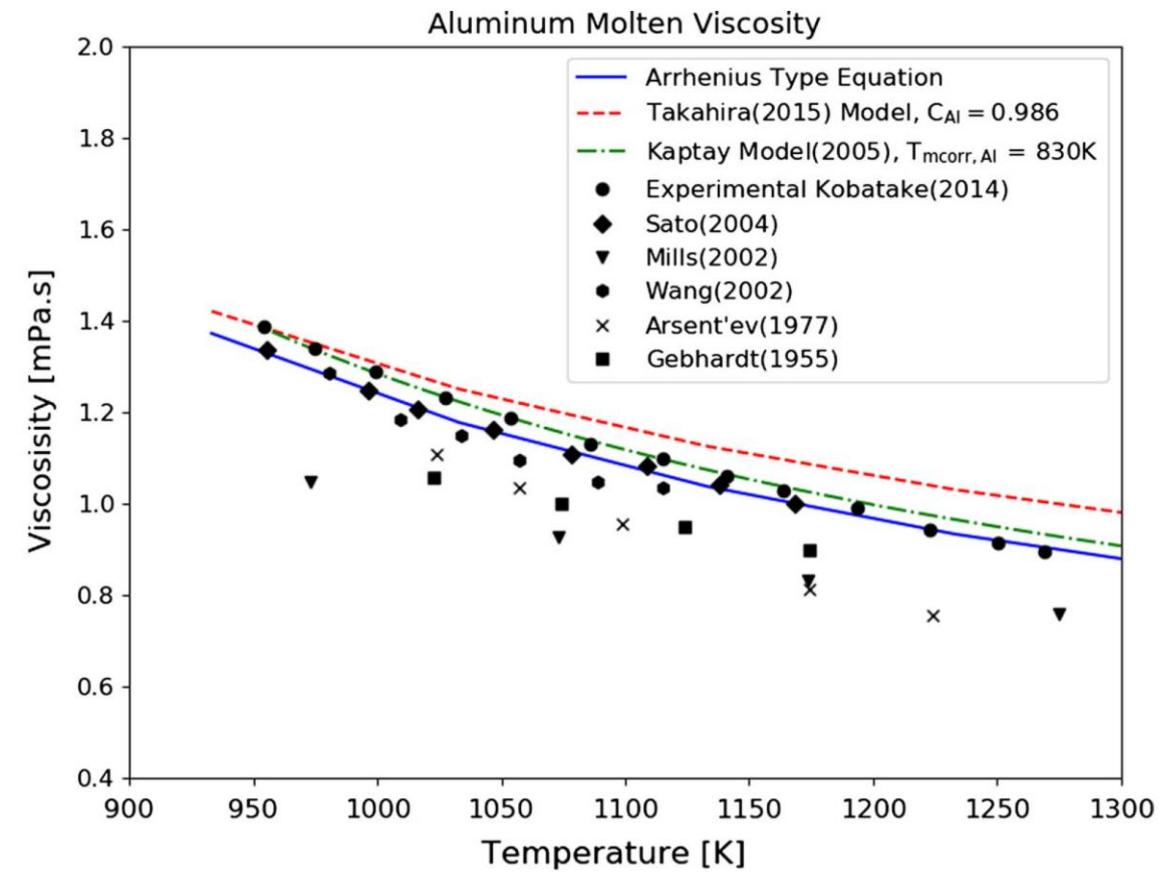
- The molecules are closer together and interact more frequently
- Viscosity in liquids is due to the attractive forces between closely packed molecules, which resist movement past each other
- Unlike gases, increasing temperature in liquids typically reduces viscosity because the increased molecular motion overcomes the intermolecular forces
- **As temperature increases, liquid viscosity usually decreases** because the higher thermal energy allows molecules to overcome the attractive forces that keep them in place



The efficient engineer, <https://youtu.be/VvDJyhYSJv8>

Intermolecular cohesive forces are dominating the influence on viscosity

- For liquids, as the **temperature increases**, the **viscosity typically decreases**
- Increased temperature generally **increases the energy of the liquid molecules**, which then can more easily **overcome intermolecular forces**, allowing them to move more freely past one another
- Simulation of casting processes demands accurate information on thermophysical properties for selected alloys; this is particularly relevant for multi-component alloys
- Several models can be found in the literature, such as those in the form of Arrhenius-type equations; models still depend on the availability of experimental data
- A considerable discrepancy between experimental data and simulated results is frequently observed for some pure metals



[FER19] Ferreira, I.L., de Castro, J.A. & Garcia, A. (2019): On the prediction of temperature-dependent viscosity of multicomponent liquid alloys. *Continuum Mech. Thermodyn.*, 31, pp.1369–1385

- Like all thermally activated processes, the temperature dependence of viscosity for liquids can be expressed by a relationship similar to the Arrhenius equation, also known as the **Andrade equation**:

$$\eta(T) = \eta_0 \exp\left(\frac{E_A}{RT}\right) \quad \text{Eq. 1.5.7}$$

where:

η_0 = Reference dynamic viscosity at temperature T_0 [Pa·s]

T = Temperature [K]

E_A = Activation energy in [J/mol]

R = Universal gas constant [J/(mol K)]

- Andrade equation underestimates the temperature dependence of viscosity
- Andrade equation as well as other, much more complex but also more precise models, require the **specification of experimentally determined, material-specific constants**

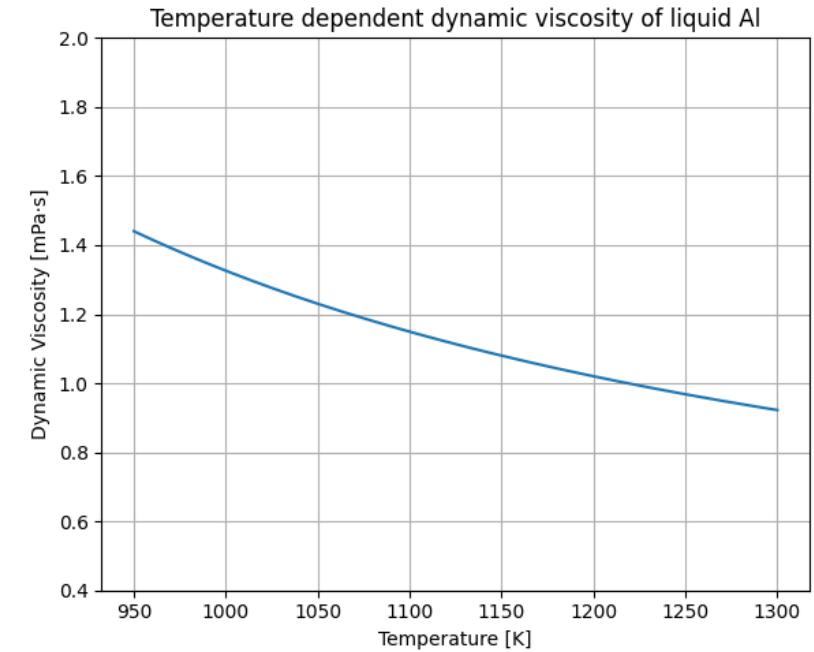


TABLE I Data for the viscosity of relevant elements drawn from two compendia [22, 23]

Element	M.Pt [3] T_m (°C)	$\eta(T_m)$ (mPa·s)	η_0 (mPa·s)	E (kJ mol ⁻¹)	$\rho(T_m)$ [3] (kg·m ⁻³)
Al	660	1.38	0.257	13.08	2380
[DIN04]		1.30	0.149	16.5	

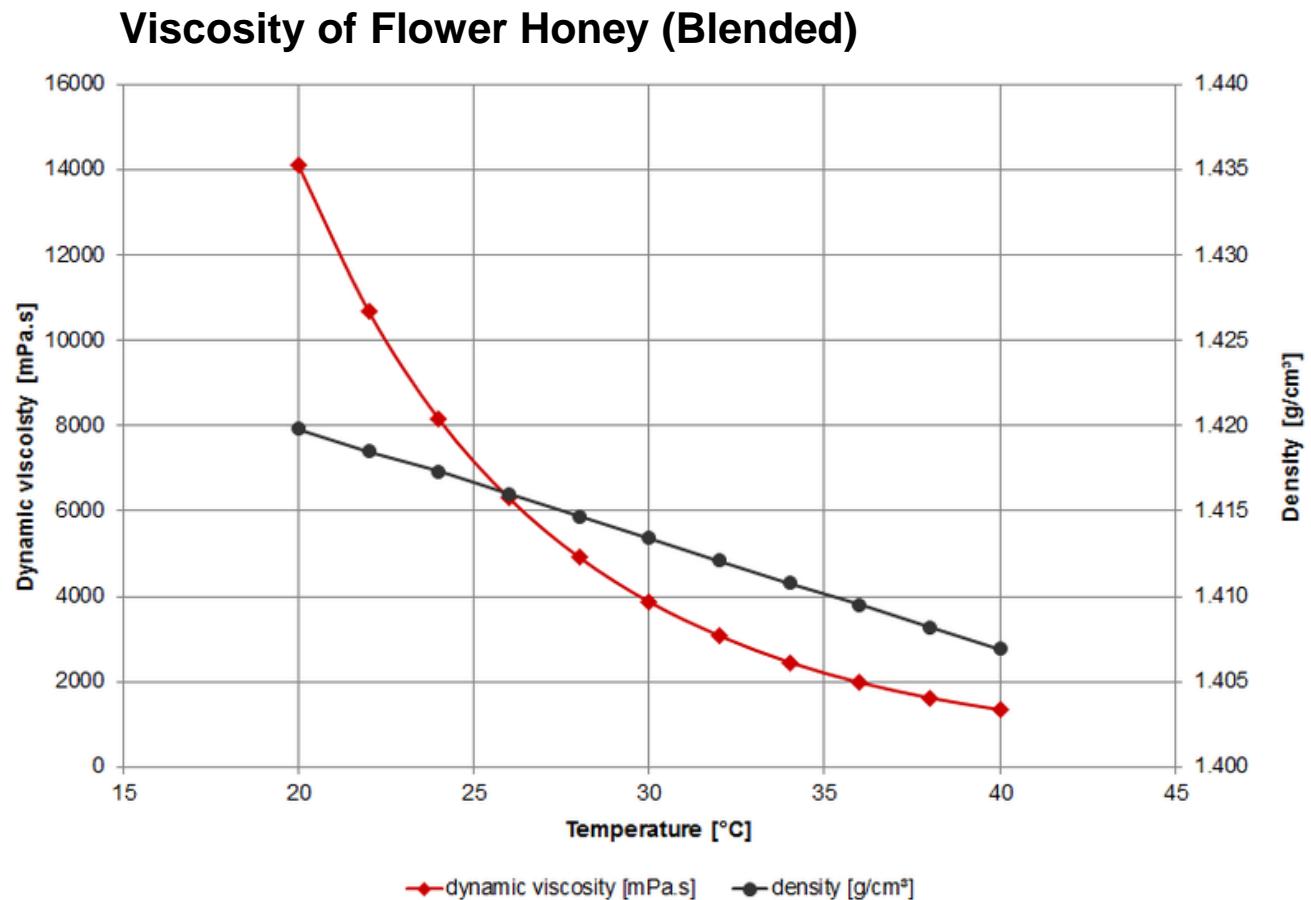
[DIN04] Dinsdale, A.T. & Quested, P.N. (2004): The viscosity of aluminium and its alloys – A review of data and models. Journal of Materials Science, 39(22), pp.7221–7228

- Definition of the Reynolds number, influence of the viscosity term in the denominator on the Reynolds number:

$$Re = \frac{\rho u L}{\eta} = \frac{\text{Intertial forces}}{\text{Viscous forces}}$$

Eq. 1.5.8

- High viscosity → laminar flow (low Reynolds number)
- Let us illustrate this using the example of the viscosity of Flower Honey (Blended)
- Temperature dependent data from Anton Paar:
<https://wiki.anton-paar.com/en/flower-honey-blended/>

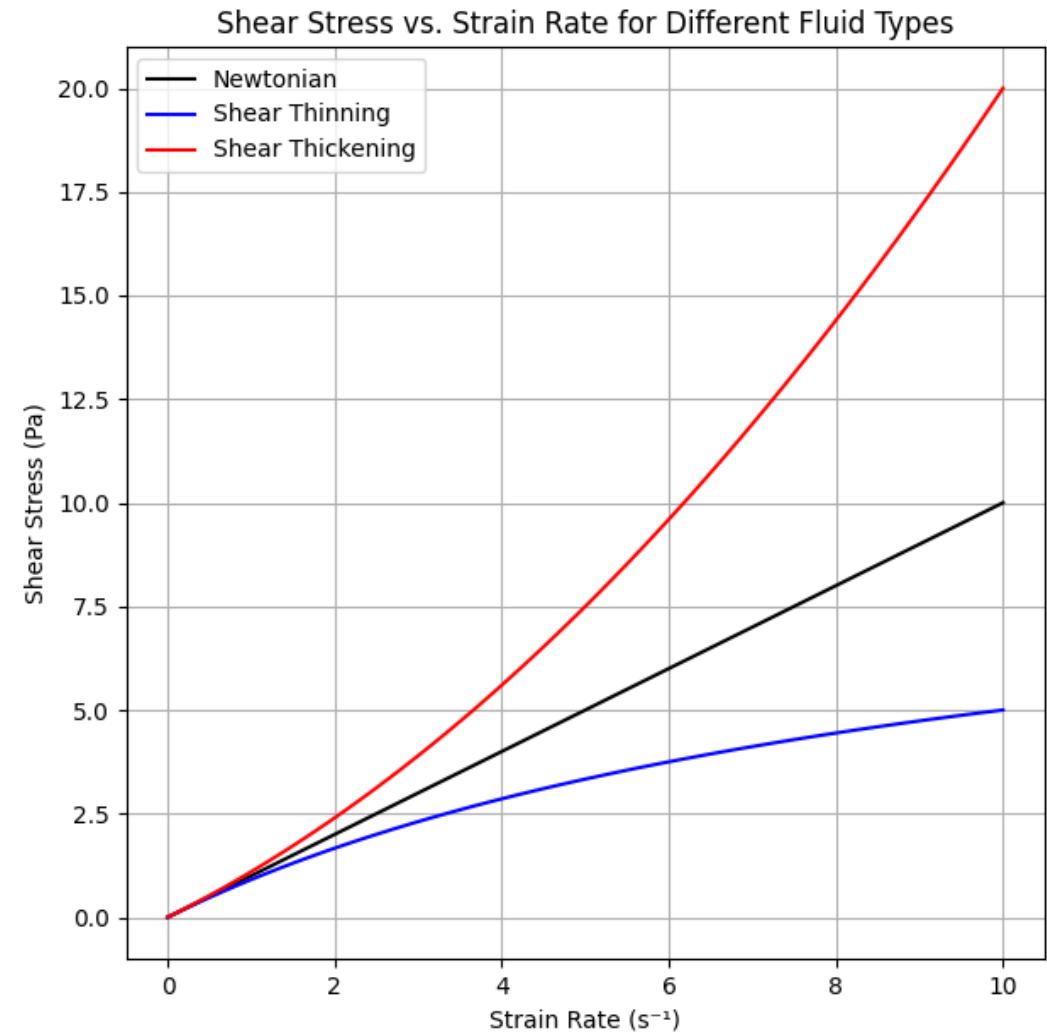


Basics

- As introduced before:

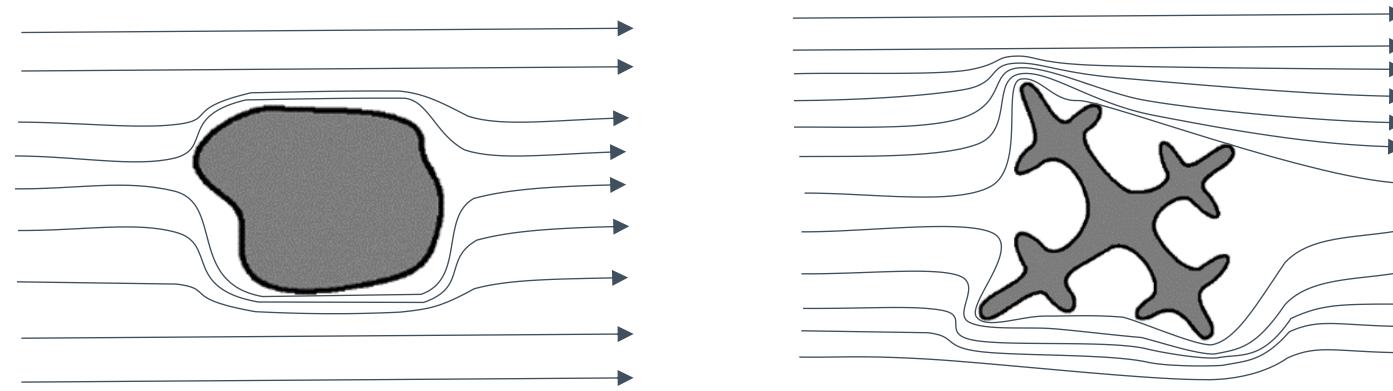
$$\tau = \eta \cdot \dot{\gamma} \quad \text{Eq. 1.5. 4}$$

- For a **Newtonian fluid**, the relationship between shear stress and strain rate is linear and can be described by Newton's law of viscosity (Eq. 1.5.1)
- For **shear thinning** (pseudoplastic) and **shear thickening** (dilatant) fluids, the **relationship is not linear**
- **Shear thinning** fluids exhibit a **decrease in viscosity** with increasing strain rate; **shear thickening** fluids show an **increase in viscosity**



The **homogenization processes** caused by the flow also have an effect on the **flow behavior** of the molten metal by changing the **solidification morphology**

- With increasing flow, “smoother” spherical grains are formed instead of “rough” dendritic grains
 - The smoother the surface, the lower the flow resistance of the grains, i.e., the viscosity of the molten metal decreases with the smoothness of the surface of the grains present
 - The viscosity of molten metal depends on the flow-related solidification front of the grains
- The **viscosity** of molten metals is therefore dependent on **shear rate** and **time** (= thixotropic)

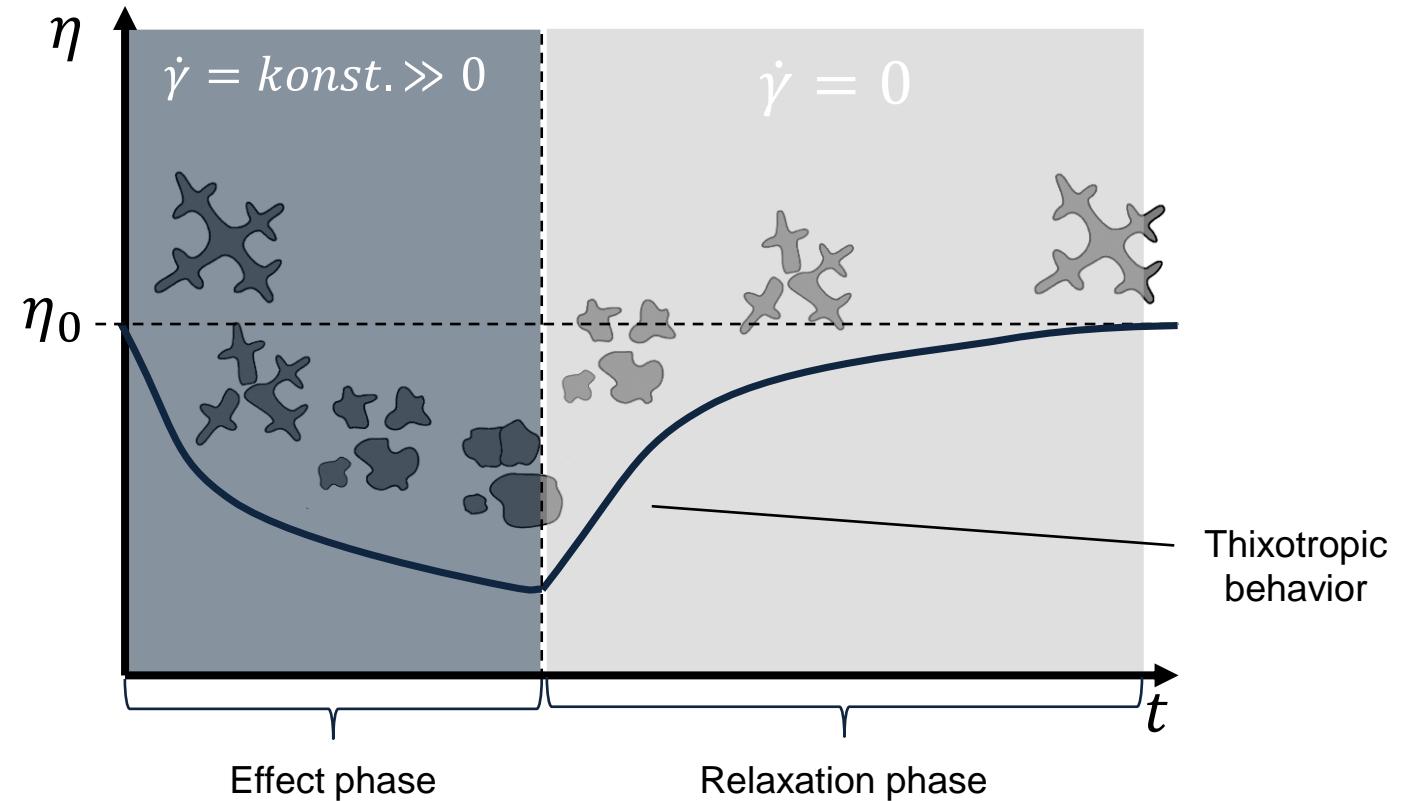


Schematic 2D flow diagram of grains with different morphologies

Definition of thixotropic behavior

- While the viscosity of Newtonian media changes neither with time nor with the shear rate, the viscosities of shear-thinning and shear-strengthening media change directly with the shear rate, independent of time
- The viscosity of a thixotropic material depends on the shear rate and time

- During constant shear stress, the viscosity of the thixotropic medium decreases with time
- After the end of the shear stress, the viscosity of the thixotropic medium increases again over time to the initial level

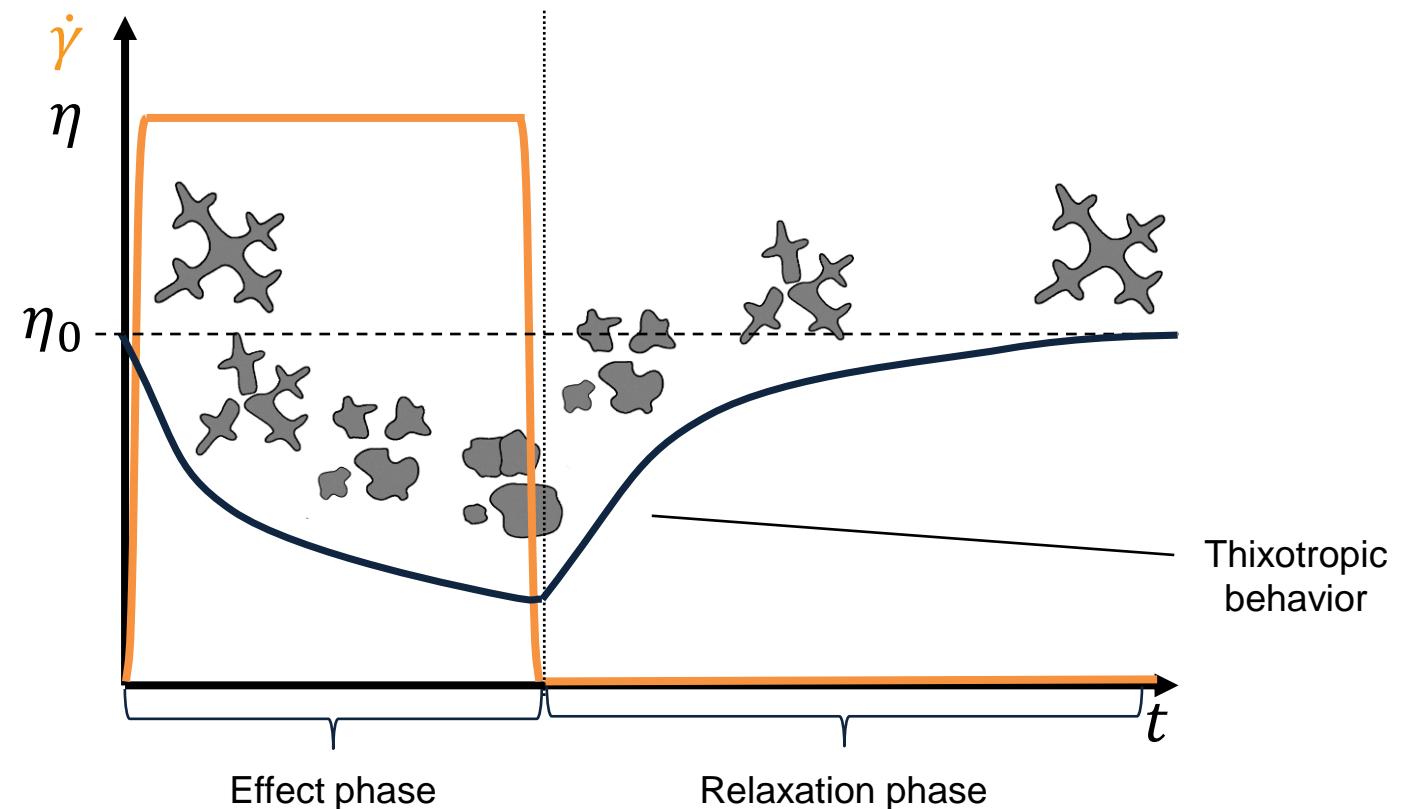


Definition of thixotropic behavior

As explained above, the surface of the grains changes due to the **change in concentration of the melt** surrounding them and the resulting change in the solidification front

Procedure:

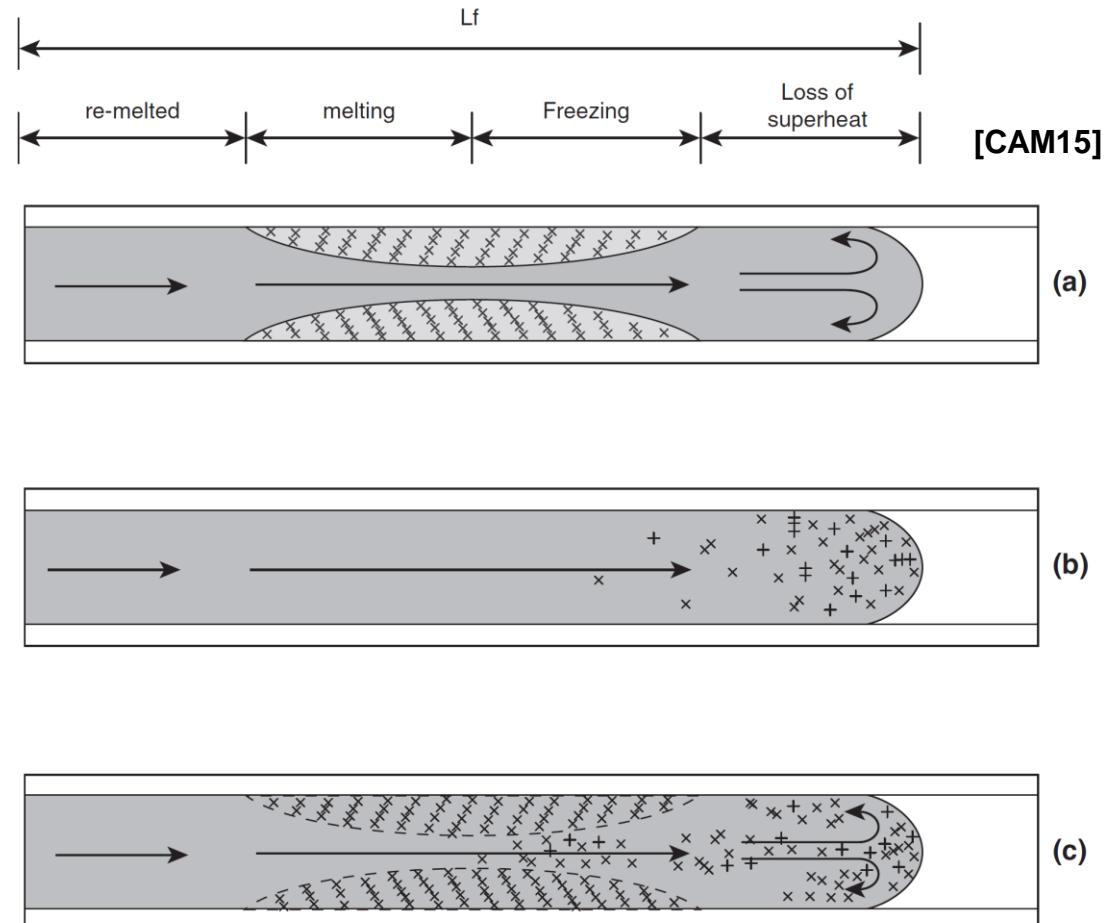
- During constant shear stress, the concentration build-up around the grains is increasingly reduced and the dendrite tips are melted
- After the end of the shear stress, the concentration build-up around the grains increases again due to the lack of mixing



Melt Rheology

Metal flow in narrow areas

- Typical Behavior: Most pure **liquid metals**, such as aluminum, exhibit Newtonian behavior where viscosity is constant, regardless of the shear rate
- Non-Newtonian Exceptions: In special cases, such as during **high-shear processing** or when metals are in a **semi-solid state**, **non-Newtonian behaviors** like shear thinning **can occur**
- In Metal Processing (High-Speed Casting): Shear thinning can enhance metal flow into molds, reducing casting defects
- **Predominantly Newtonian:** Despite these exceptions, pure liquid metals like aluminum usually maintain Newtonian characteristics under most processing conditions
- **Semi-Solid Metal Processing:** In processes such as thixomolding and thixocasting, where metal is partially solid, **shear thinning** is more pronounced due to the interaction between solid and liquid phases



Some models for solidification during mold filling

Objective

- Fluidity tests measure the ability of a molten metal to fill intricate features of a mold before solidifying

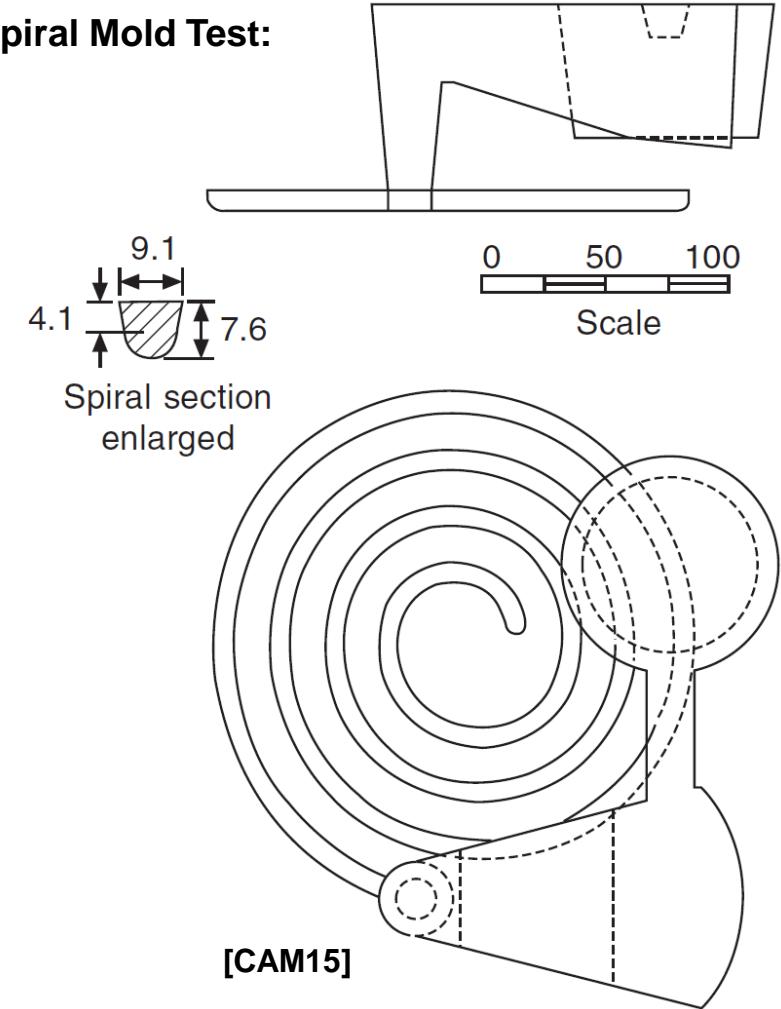
Importance in Casting Technology

- **Determines Quality:** High fluidity ensures the casting can replicate detailed designs without defects
- **Material Characterization:** Fluidity varies among metals and alloys and depends on composition, temperature and ambient conditions

Test Methods

- **Spiral Mold Test:** A classic method where the metal is poured into a spiral cavity; the distance it travels before solidifying is measured as fluidity
- Flow Test: Molten metal is poured to fill a standardized thin section pattern until it stops flowing, assessing its fill capacity

Spiral Mold Test:

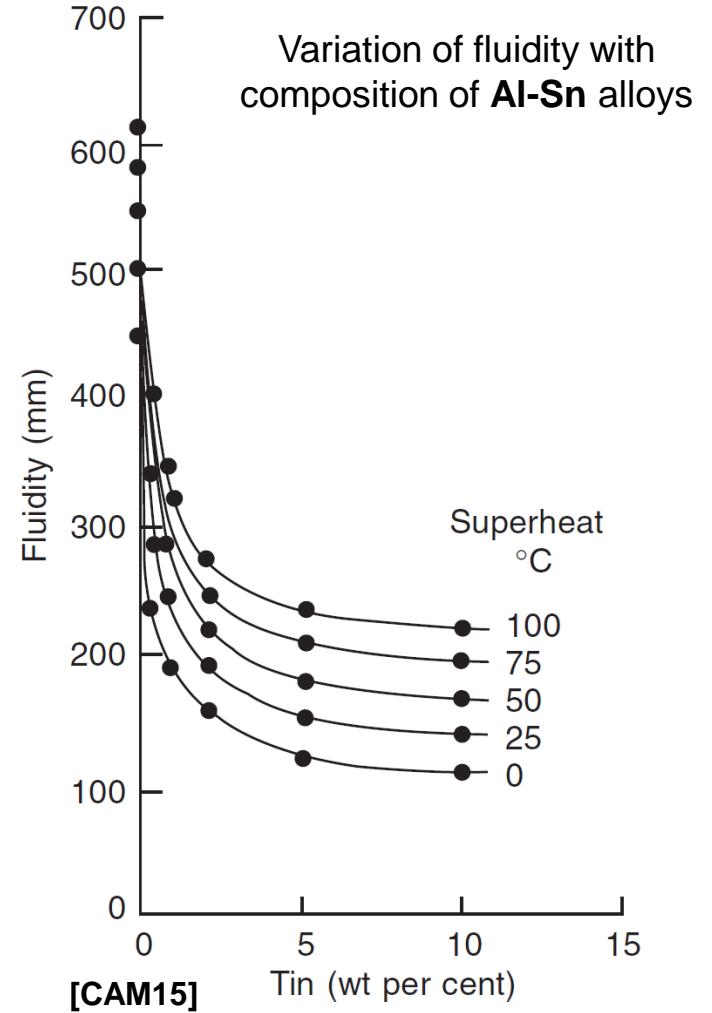


General factors that influence fluidity

- **Temperature:** Higher than the melting point increases fluidity; overheating can lead to gas absorption and oxidation
- **Viscosity:** Low viscosity metals flow better; additives and impurities can alter viscosity
- **Mold Design:** Smooth, coated molds improve flow; complex shapes can reduce fluidity
- **Atmosphere:** Protective gases can reduce surface tension and improve flow

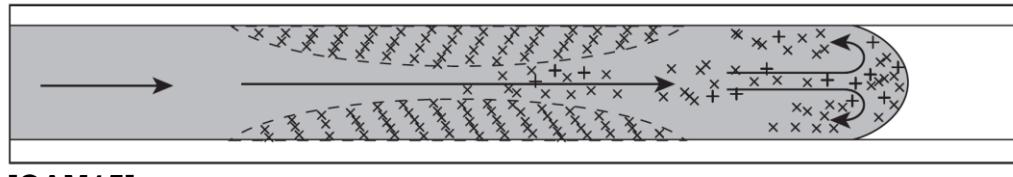
Observations

- **Effect of Superheat:** At 0°C superheat, fluidity is relatively low across all tin percentages; increasing superheat significantly enhances fluidity due to reduced viscosity and delayed solidification
- **Alloy composition:** As tin is added to aluminum, it forms a series of intermetallic compounds; these compounds can disrupt the liquid structure, increase viscosity, and hence, reduce fluidity

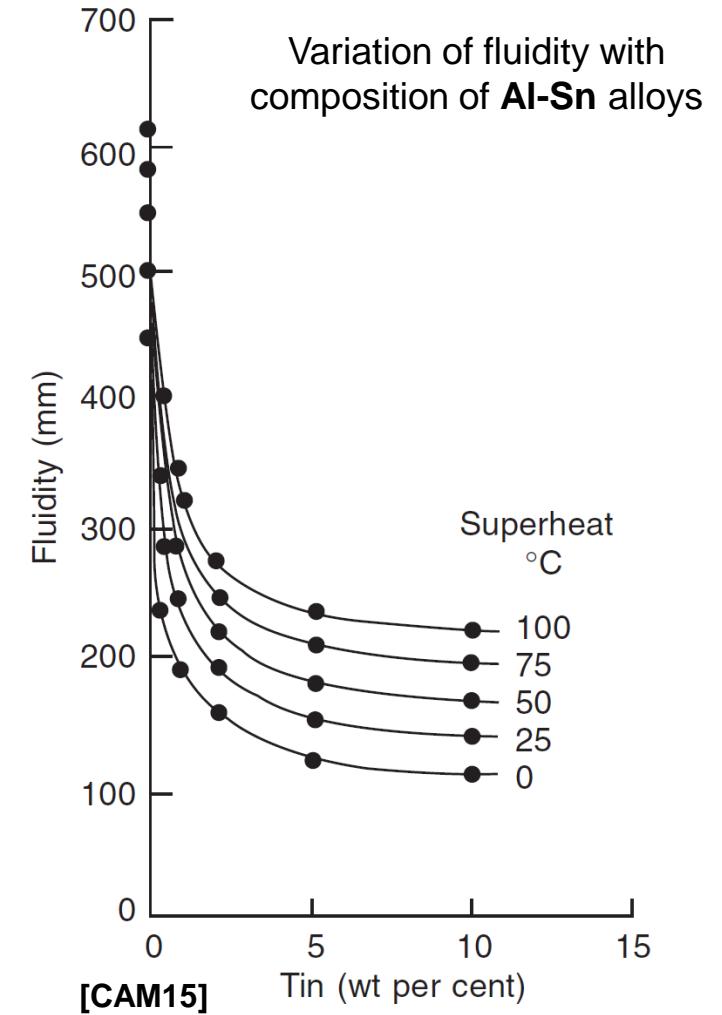


Material properties that influence fluidity

- **Composition effect:** Tin addition forms intermetallic compounds, raising viscosity and reducing fluidity
- **Superheat influence:** Higher superheating generally enhances fluidity, but fluidity still drops with more tin at all superheat levels
- **Solidification impact:** More tin widens the solidification range, causing early solid particle formation that impedes flow
- **Eutectic behavior:** Initial tin additions lower melting point up to eutectic composition; beyond this, higher-melting phases decrease fluidity
- **Surface tension and wetting:** Changes in alloy composition affect surface tension and mold wetting, crucial for flow into mold details



[CAM15]

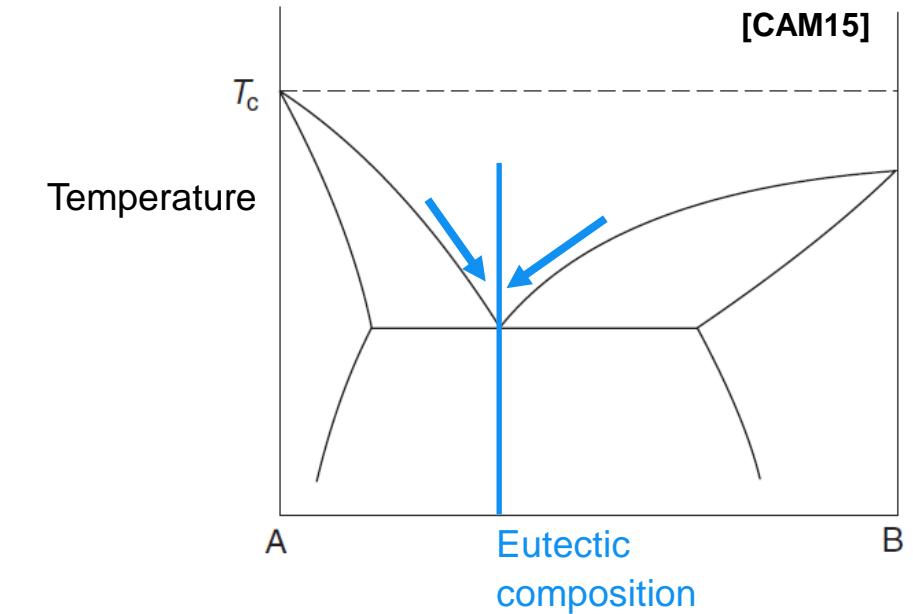


Fluidity at zero-superheat

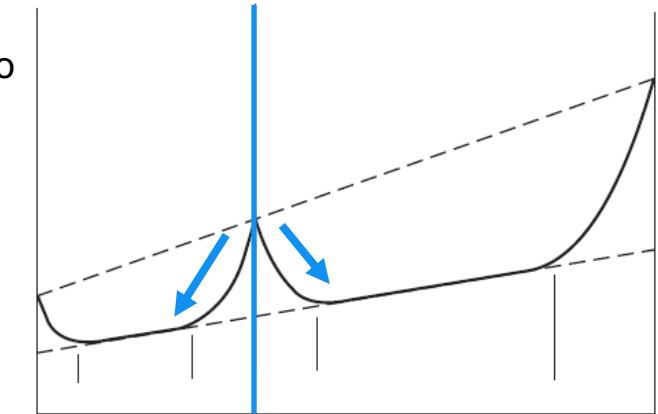
Eutectic Point: Additives lower the melting point up to the eutectic concentration, beyond which higher-melting intermetallics form, affecting fluidity

Solidification Range: Alloys with compositions away from the eutectic point have an extended solidification range, which can hinder fluidity as early solidification occurs

Phase Formation: Non-eutectic compositions promote the formation of primary phases before reaching the eutectic, increasing viscosity and reducing fluidity

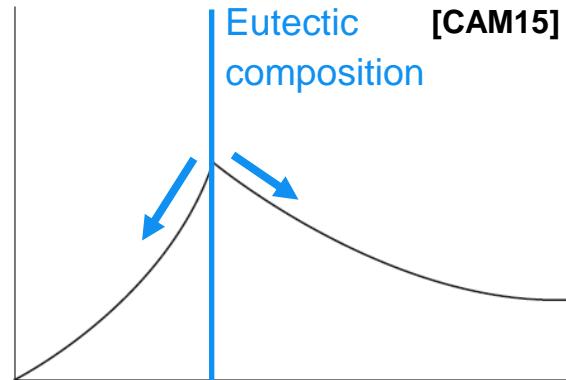


① Fluidity at zero superheat

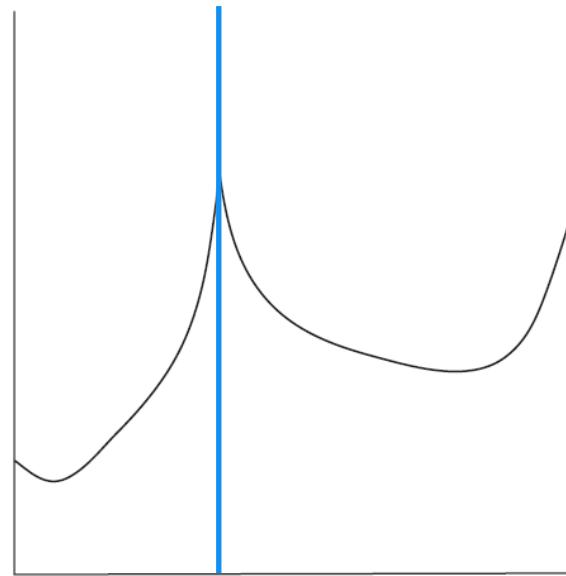


Melt Rheology

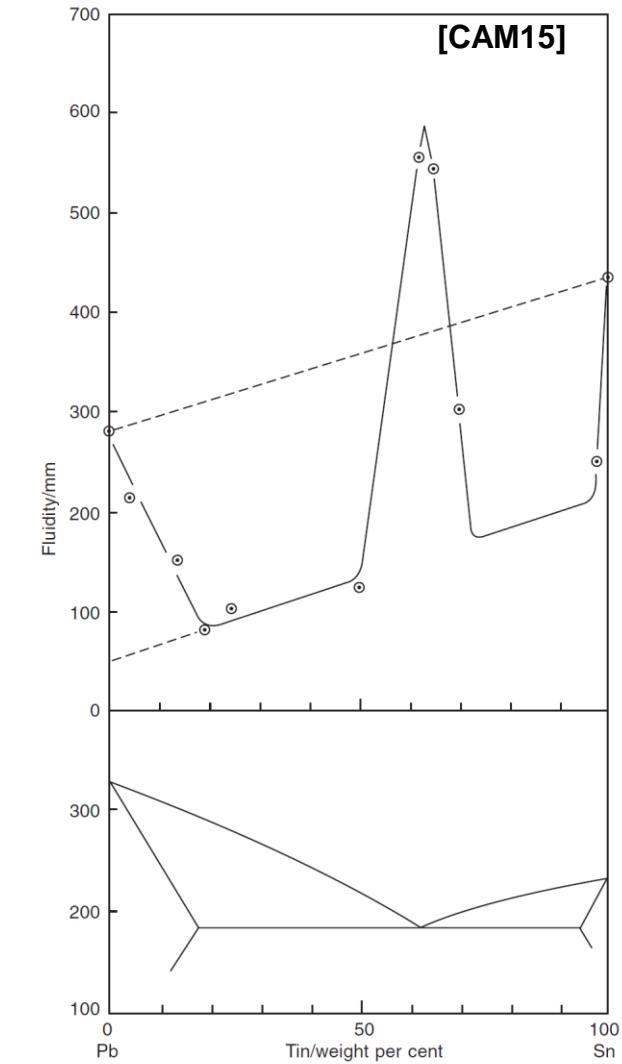
Fluidity Tests in Casting



② Additional fluidity due to superheat at temperature T_c



- Peaks in fluidity are impressively narrow → for certain eutectic alloys the fluidity is awesomely **sensitive to small changes to composition**, particularly when it is realized that this is still a simple relationship (binary alloy)
- Many alloy systems are far more complicated → further changes of fluidity performance are to be expected
- Partially explains why some castings can sometimes be filled, and at other times not → changes in alloy composition (batches of alloy)
- Clearly, to maximize reproducibility, deviations in alloy composition must be reduced/ measured

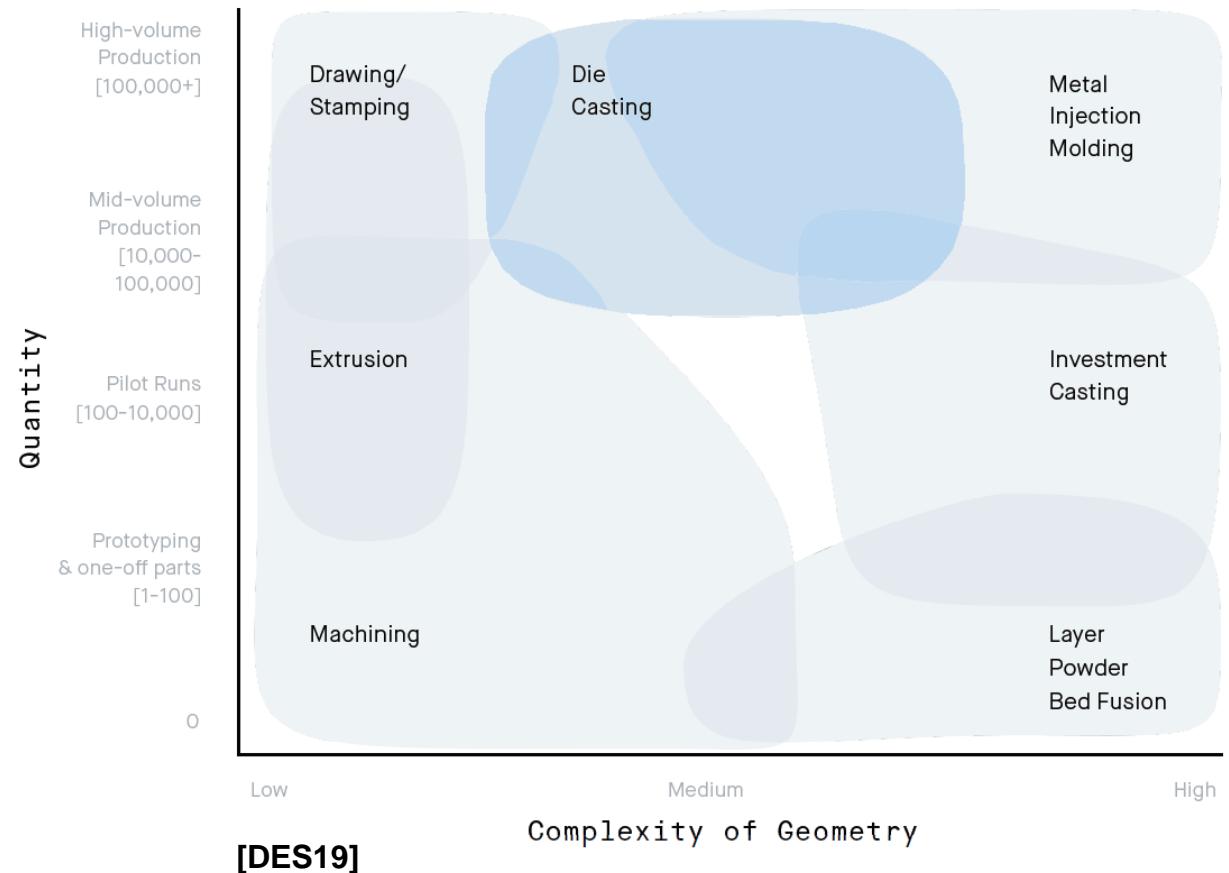


Chapter 2: Casting processes

Casting processes

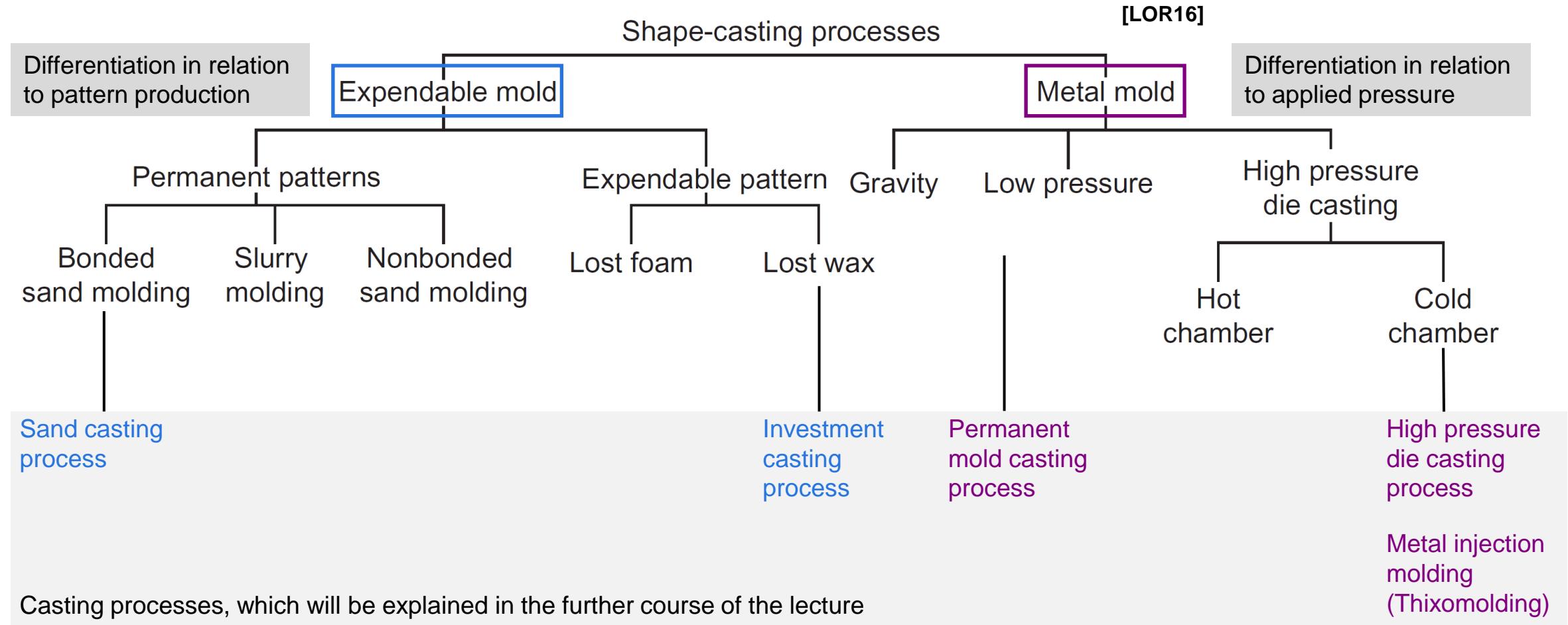
Diversity in Manufacturing

- Different casting processes match **specific volume needs**, from single prototypes to mass production
- **Complexity** handling varies by process: die casting excels in detailed parts, while extrusion suits simpler shapes
- High-volume suitability for die casting, contrasted with investment casting for smaller runs
- Investment casting and metal injection molding provide high geometric precision
- Die casting is typically for non-ferrous alloys; other processes offer broader material choices
- Drawing/stamping and extrusion are more cost-effective at higher volumes
- Layer powder bed fusion offers **high complexity with material flexibility** in advanced manufacturing



Casting processes

Overview – Shape casting categories and methods



Chapter 2.1: Sand casting

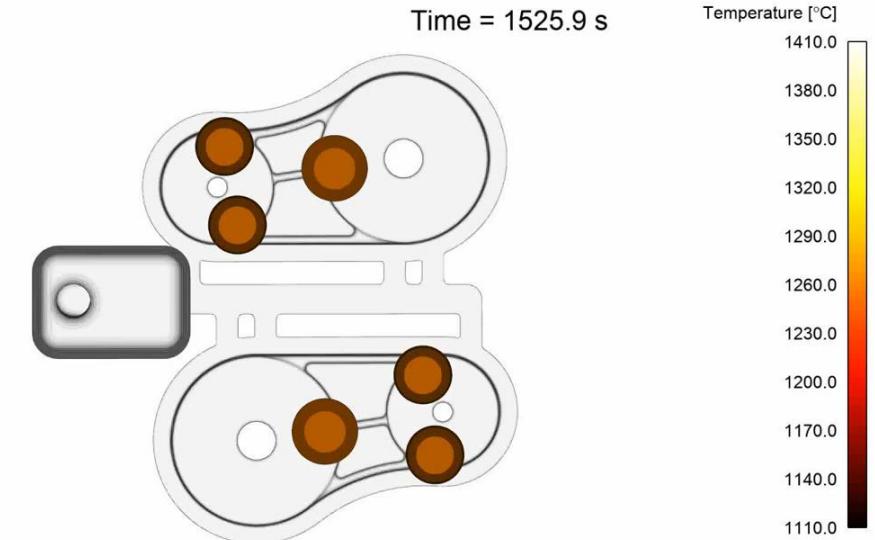
Casting processes

Process description

- The **melt is poured** into the pouring basin or cup
- The melt flows down the sprue, through the **gating system** including gates and runners.
- It then enters the riser and **mold cavity**, which has a **core** for internal features.
- **Vents** in the mold allow air to exit effectively during filling.
- A **filter** within the mold captures inclusions in the melt.
- As solidification occurs, the **riser** feeds the mold cavity to counteract solidification shrinkage

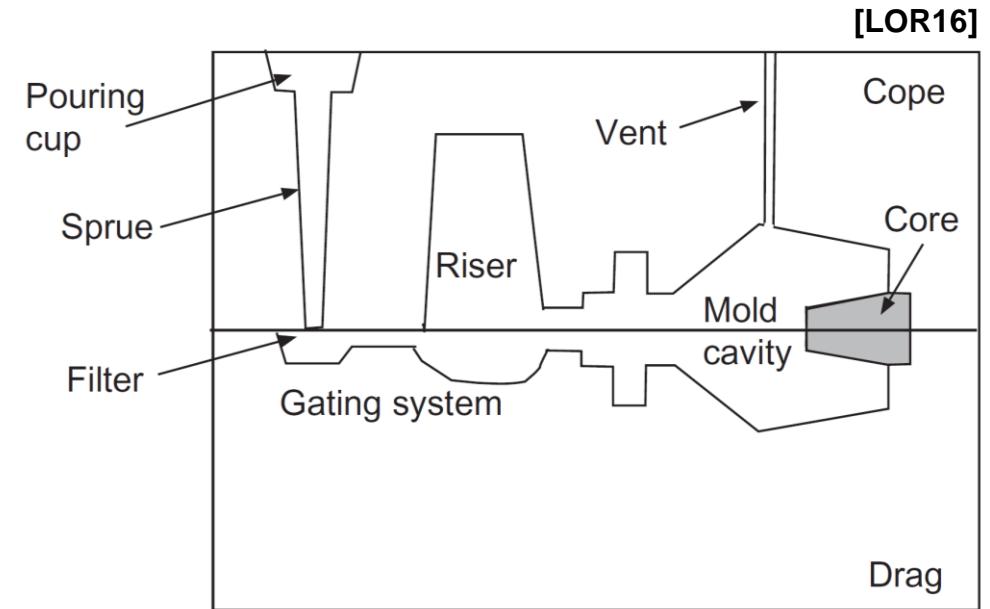
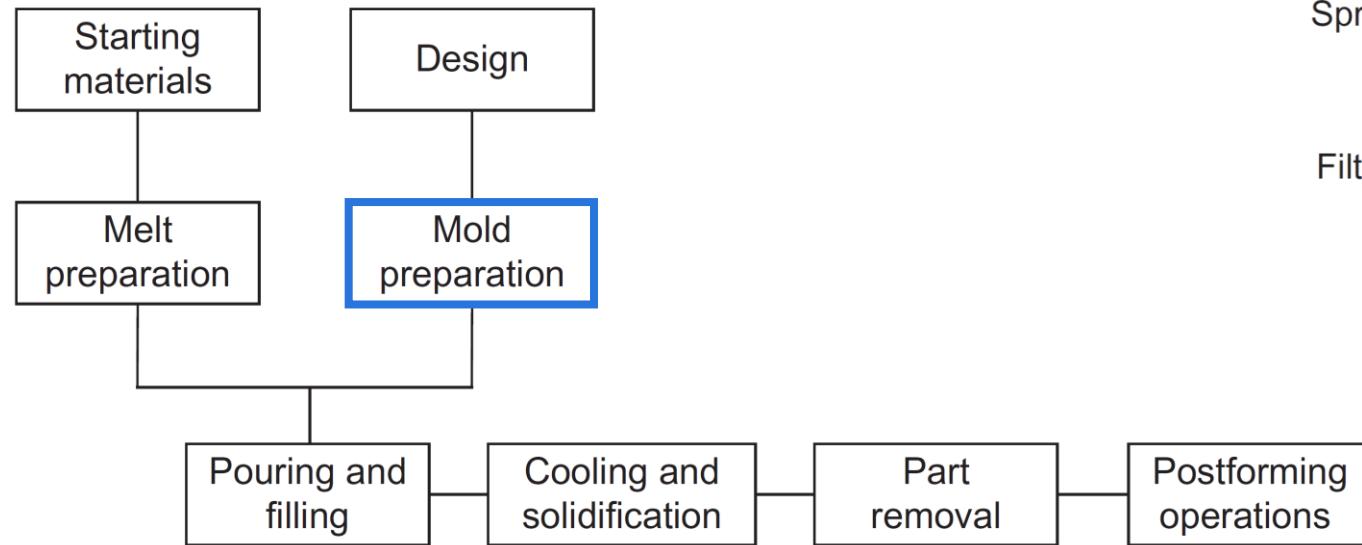
FLOW-3D[®]
CAST

GRAVITY SAND CASTING



Casting processes

Mold preparation



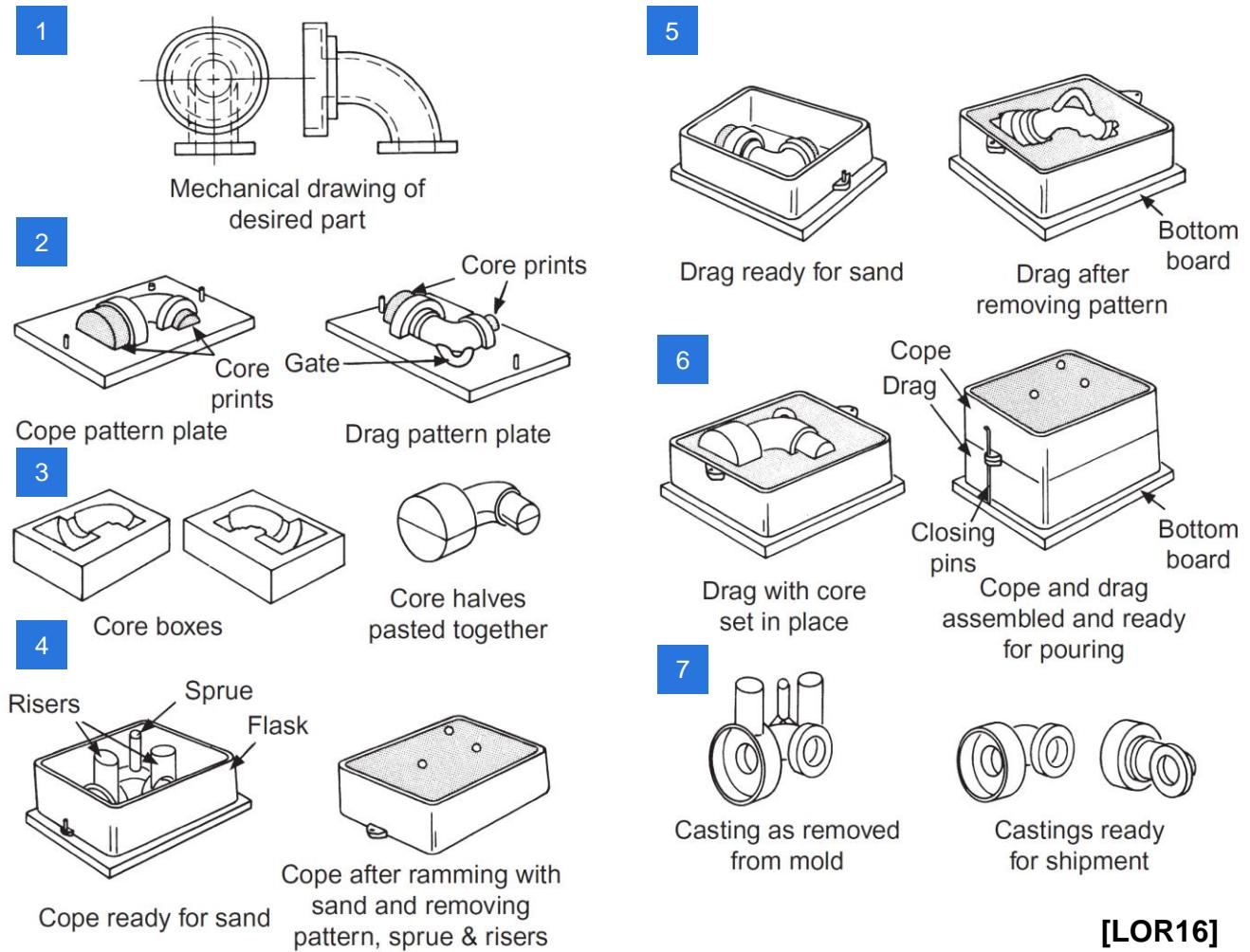
Schematic diagram and naming conventions of a sand casting mold, detailing the upper half (cope), lower half (drag) and core

Flow diagram for shape casting by the sand casting process as an example

Casting processes

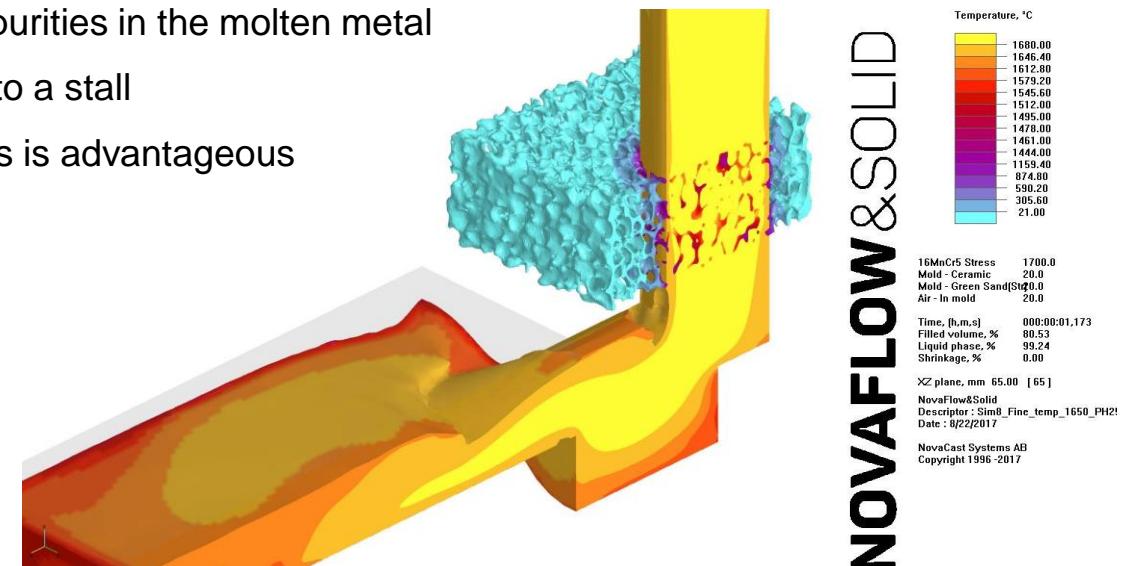
Mold preparation

- Design mold features and fabricate a pattern (2) (usually in metal or plastic) detailing internal features, including the mold cavity; pattern may be simple (single piece for each mold half) or complex (multiple pieces)
- Fabricate core box (3), then use it to create the core in two sand pieces
- Compact sand mix in the flask around the cope pattern, often with inserts for the sprue, pouring cup, and sometimes a riser, remove pattern and inserts (4)
- Follow a similar process for the lower half of the mold, known as the drag
- Carefully place the core, then assemble the two mold halves (6)



[LOR16]

- Used to **retain inclusions** like **slag**, foam, or **oxides** from melt flow in gate systems
- Help **homogenize** and **decelerate metal flow**, reducing re-oxidation and sand erosion risk
- Ceramic filters are common, differentiated into **ceramic foam** (pore structure from foaming) and **cellular ceramics** (pore structure from pressing)
- Filter materials include zirconium silicate, zirconium oxide, silicon carbide, and mullite
- Thicker filters **increase flow resistance**, affecting mold filling time and casting quality
- Filter size selection depends on casting temperature, pore size, and impurities in the molten metal
- Accumulated impurities increase filter flow resistance, possibly leading to a stall
- In larger castings, using multiple filters across several casting processes is advantageous



Pressed Filters

- + High reproducibility due to manufacturing method, ensuring consistent characteristics; strong, can withstand high flows; suitable for large castings
- Risk of non-laminar flow after filtering, unlike foam filters; creates small streams of metal

Foam Filters

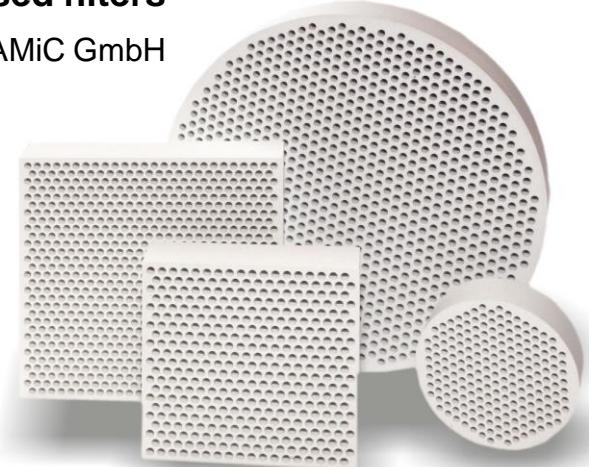
- + Effective in filtering the melt and creating laminar flow
- Low reproducibility between and within manufacturers and batches due to manufacturing method; challenging for large castings due to potential breakage and scalability issues

Woven Filters

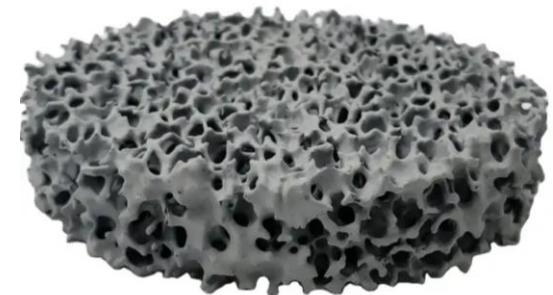
- + Easy to apply and inexpensive
- Only filters large particles; not effective in reducing the speed of the flow

Pressed filters

Source: hofmann CERAMiC GmbH



Foam filter



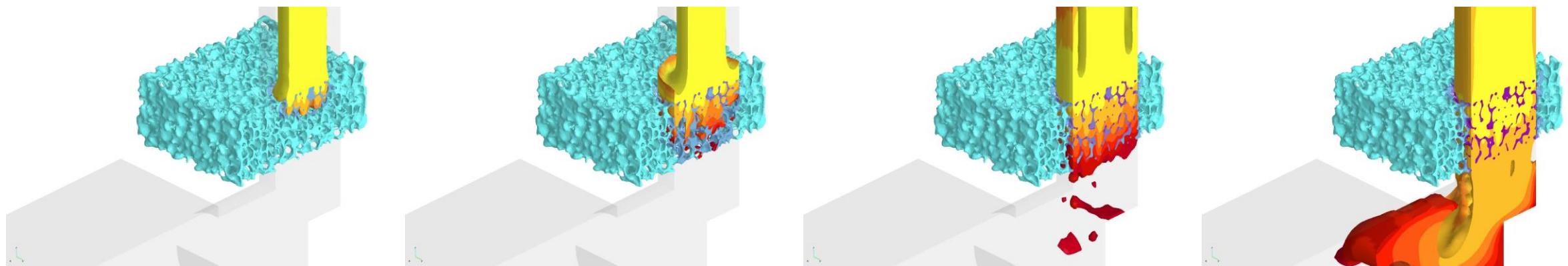
Woven filters



Casting processes

Simulation of fluid flow using casting filters

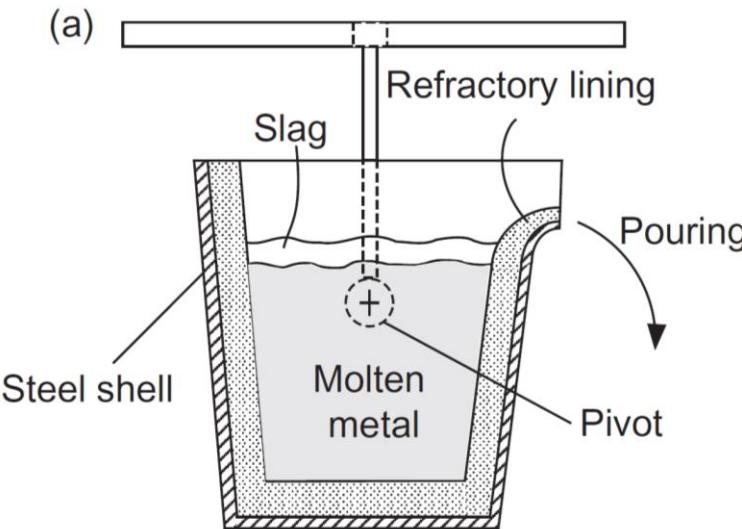
- Real dimensions in casting filters allow for accurate simulations of pressure drop and friction without estimating values
- It's critical to use the correct dimensions and filter materials to achieve the desired speed, pressure loss, and temperature drop
- Accurate simulation helps determine if the initial melt can successfully penetrate the filter, addressing a common issue
- The image sequence shows a foam filter's cross-section being heated during filling, mimicking real-life conditions
- Simulation of **pressed** and **foam filters** can be done using Finite Volume Method (FVM); increase of modelling and calculation efforts



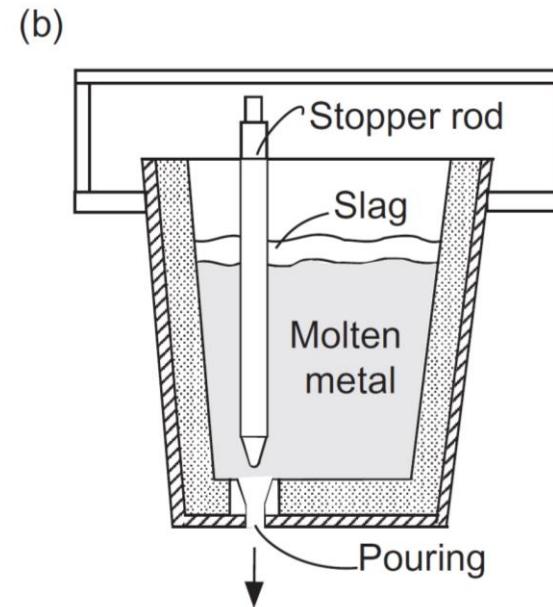
Source: NovaCast SE

Ladles for molten metal transfer

- Final adjustments to temperature and composition of the melt are made in the ladle, which can be automated
- Bottom pouring ladles are advantageous as they pull metal from below the surface, reducing inclusion of slag
- Melt streams from ladles can be shrouded to reduce oxygen exposure, essential for reactive metals like magnesium alloys
- Mold filling uses gravity to direct the melt through design features, preventing air entrainment and minimizing turbulence



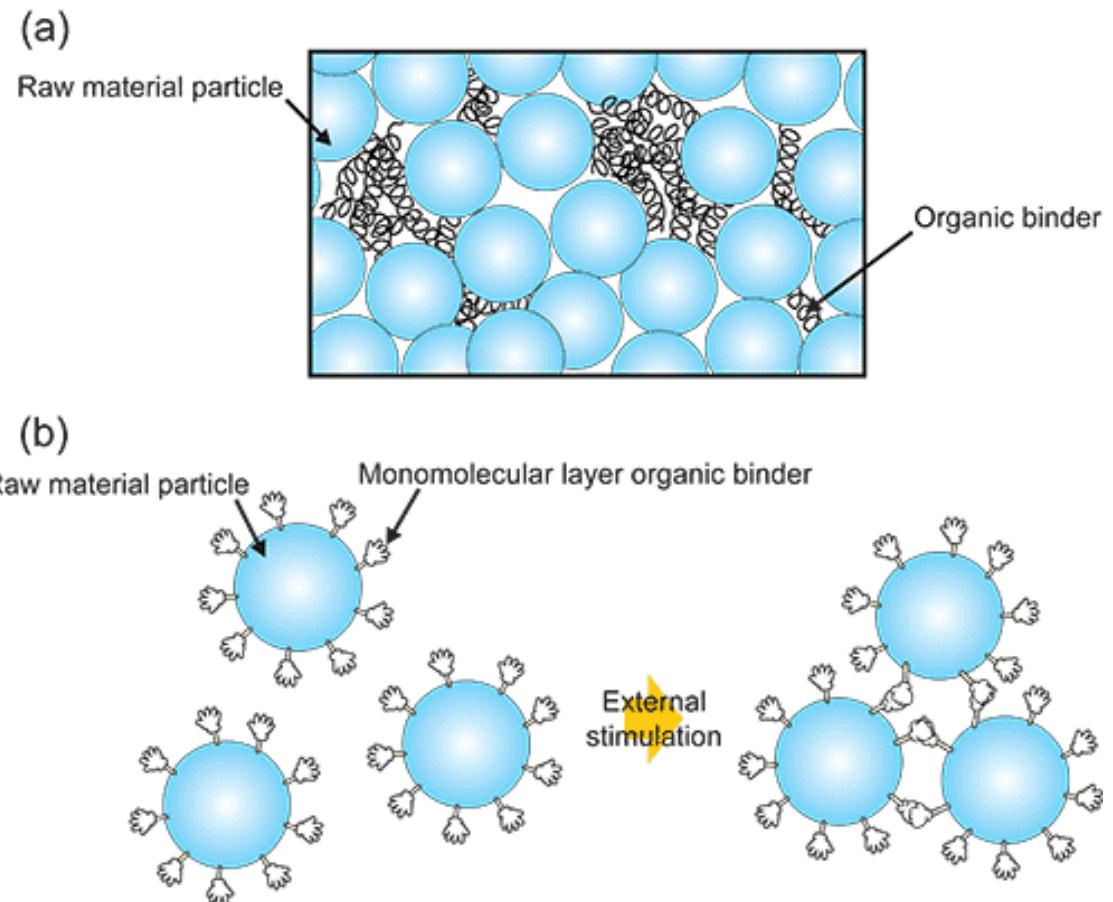
[LOR16]



(a) standard ladle with rotational axis
(b) (bottom pouring ladle).

Required binders

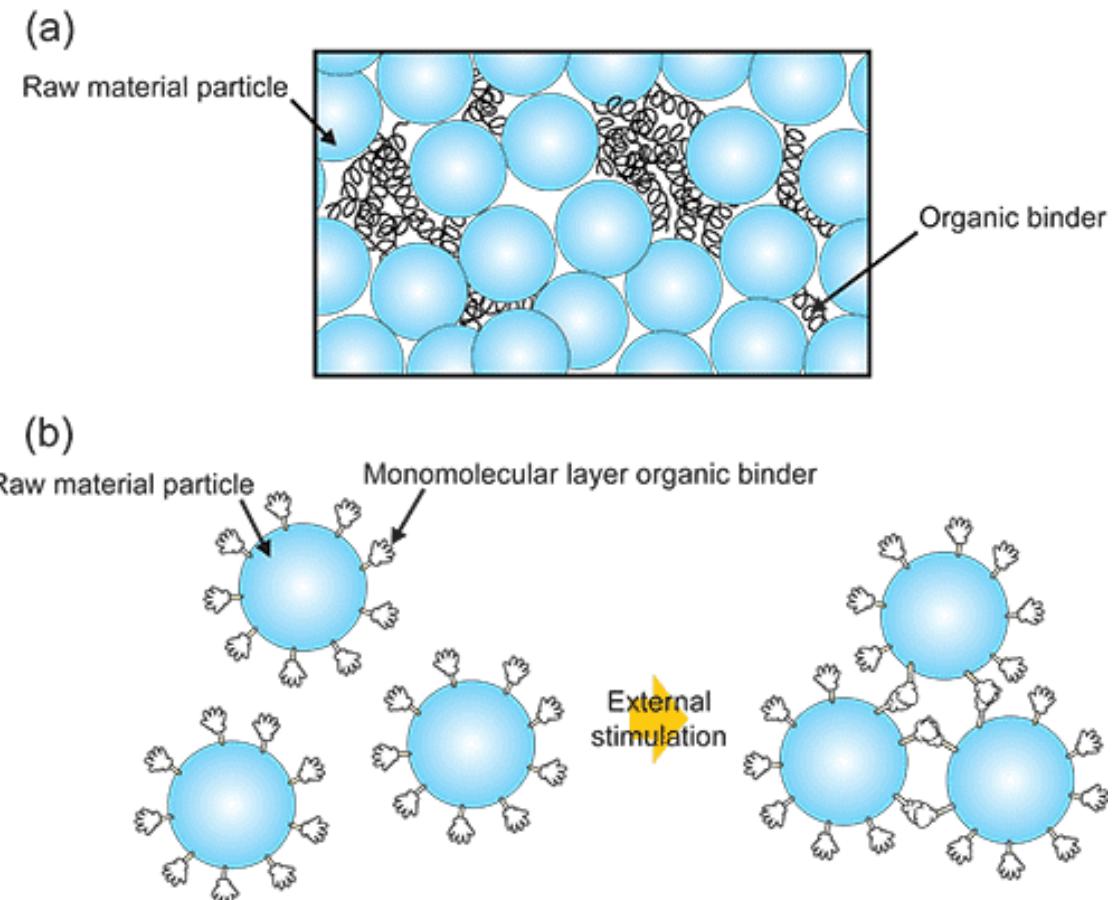
- **Function of binders:** Binders in sand casting ensure sand grains adhere together to form molds and cores, affecting the casting's finish and integrity
- **Traditional clay binders:** Clay, specifically Bentonite, offers good mold strength but can introduce gas defects due to moisture, known as **green sand casting** (→ **inorganic binders**)
- **Resin systems:** Chemical systems, like phenolic urethanes, are **activated with catalysts** (heat or chemicals) and vary in efficacy with different alloys (→ **organic binders**)
- Choice between **green and resin sand casting**



Required binders

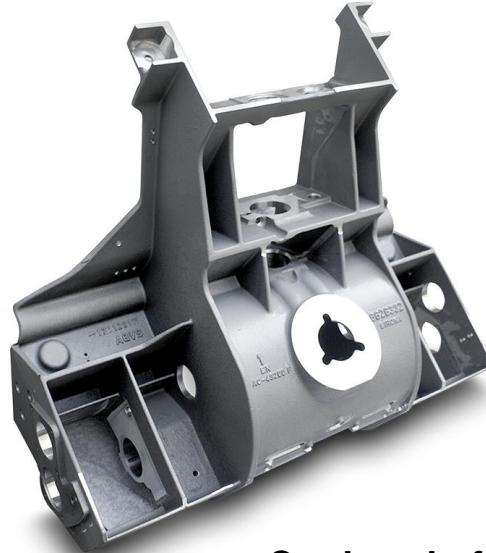
Common types of organic binders include

- **Phenolic resins:** Thermosetting plastics that become irreversibly hardened upon heating
 - **Furan resins:** Made from furfuryl alcohol, these resins are known for their thermal resistance and mechanical strength
 - **Urethane resins:** Offer excellent binding properties and flexibility
-
- + A significant advancement, providing **stronger molds** with resins activated by heat or chemicals, allowing for **finer details and superior finishes**
 - + **Lower moisture content**
 - Resin systems may require longer curing times, impacting productivity
 - Stronger molds/core structures may complicate shakeout processes
 - Cost variations exist among different resins and catalysts
 - Potential environmental concerns due to the emissions of volatile organic compounds (VOCs)



Casting processes

Some sand casted parts (Aluminium alloys)



Machine bed

Alloy: EN AC-AISi10MgSF

Dimensions: 500x300x200 mm

Weight: 11,0 kg



Cardan shaft tube

Alloy: EN AC-AISi8Cu3SF

Length: 1750 mm

Weight: 24,5 kg

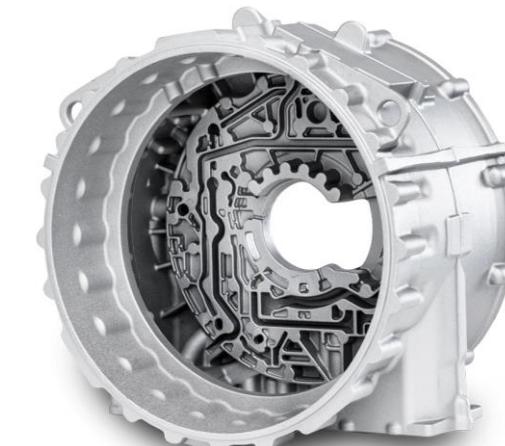


Gearbox housing assembly

Alloy: EN AC-AISi7MgST6

Dimensions: 500x300x200 mm

Weight: 100,0 kg



Converter housing

Alloy: EN AC-AISi10MgST6

Dimensions: Ø 600 mm

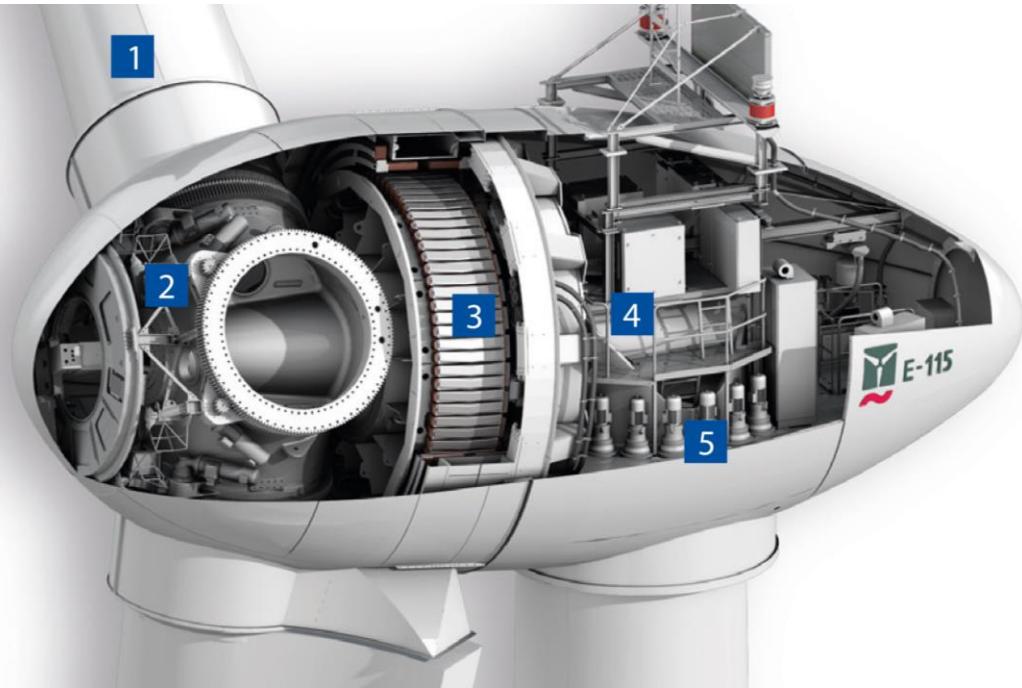
Weight: 55,0 kg



Sources: AGVS Aluminium Werke GmbH Villingen

Casting processes

Some sand casted parts



Source: ENERCON

- 1. Rotor Blade
- 2. Rotor Hub
- 3. Ring Generator
- 4. Machine Carrier
- 5. Azimuth Drive

Limitations in size only due to the mold/model construction and mainly due to the melting capacity of the furnace and the associated filling heights!

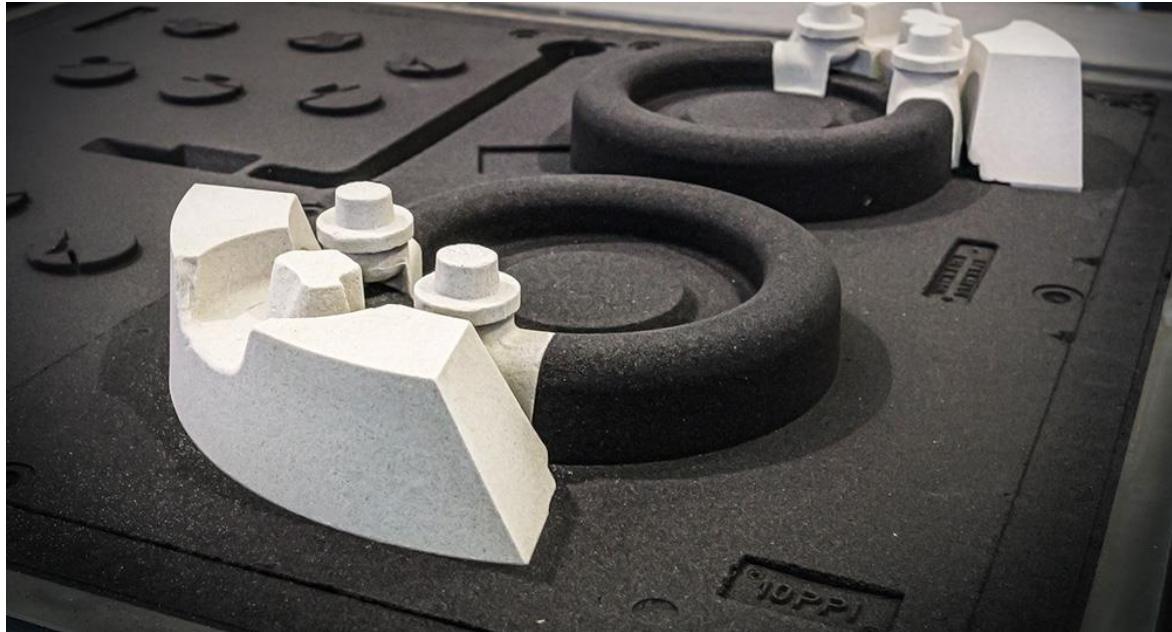


Rotor Hub, Source: Silbitz Group GmbH

Weight per piece: 500 – 45.00 kg each
Material: EN-GJS-400-18 LT

Casting processes

Some impressions of sand casting



Manufactured sand mold using different molding materials

Source: Grohmann Aluworks GmbH & Co. KG



Casting can also be automated for larger quantities. The molds are positioned on a conveyor belt and automated dosing is performed

Source: AGVS Aluminium Werke GmbH Villingen

Casting processes

Some impressions of sand casting



Handcrafted process for comparatively small, highly individualized components or component series

Source: SMP Schüßler Modell- & Prototypenbau



Highly automated process for the production of cylinder crankcases and drive components

Source: BMW AG

The sand casting process is suitable for both **large series and small quantities**.
This corresponds to the customer structure and lead to a different degree of automation.

Advantages

- + **Cost-effective for small batches:** The tooling and setup costs for sand casting are generally lower compared to other casting methods, making it cost-effective for small production runs
- + **Complex geometries:** Sand casting can produce complex shapes that would be difficult or impossible with other casting methods
- + **Large part capability:** It is capable of casting very large components that might not be possible with other types of casting processes due to equipment size limitations
- + **Wide material choice:** Sand casting allows for a wide variety of metals to be used, including ferrous and non-ferrous alloys
- + **Tooling flexibility:** Modifications to the mold are relatively easy to make and at a low cost

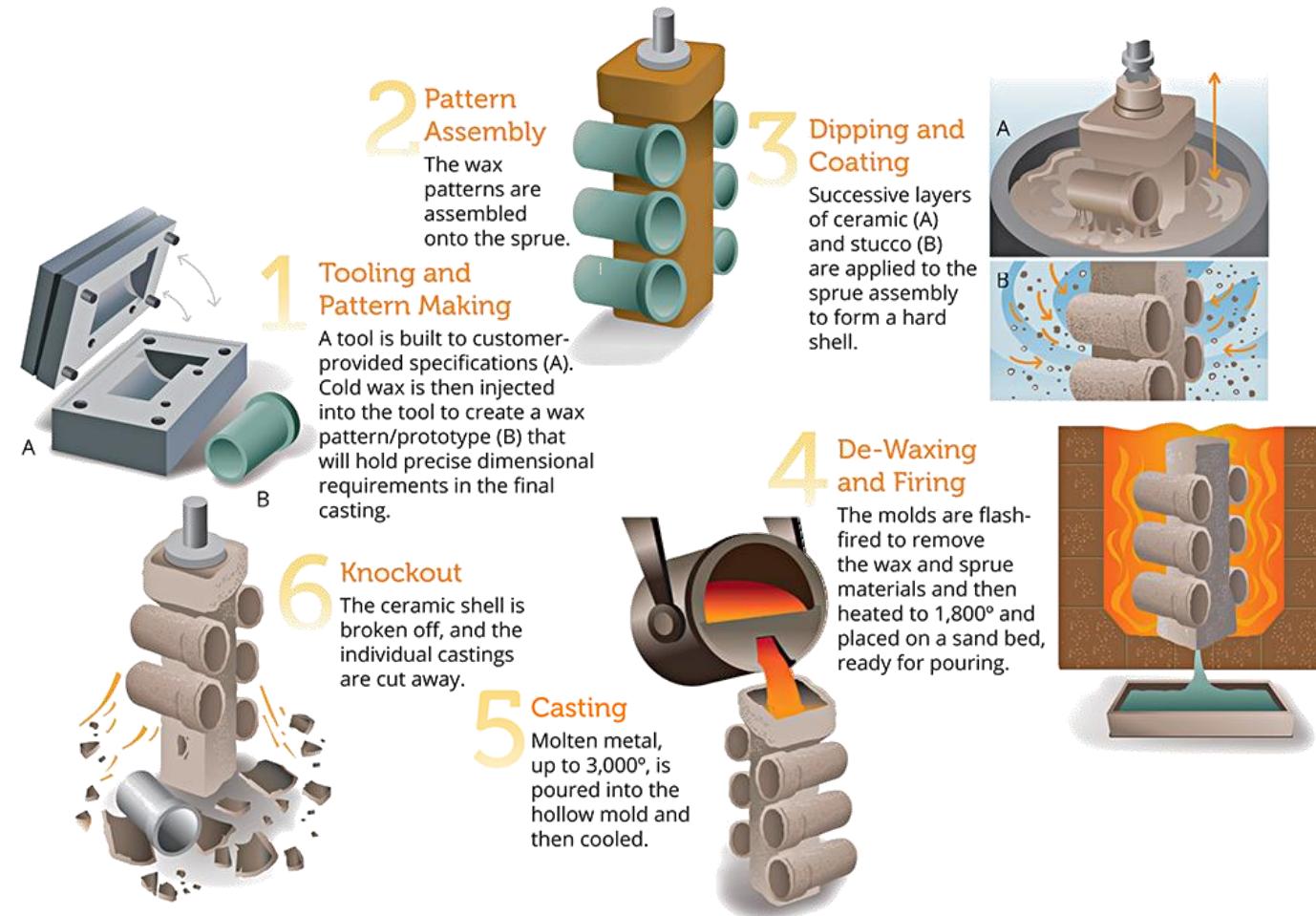
Disadvantages

- **Surface finish and tolerance:** Generally, produces a rougher surface finish compared to other methods, and the dimensional tolerances are not as tight
- **Labor intensive:** The process can be more labor-intensive compared to automated casting processes
- **Porosity:** There is a higher likelihood of porosity in sand castings, which can affect the mechanical properties of the cast part
- **Mold deterioration:** Since the mold is made of sand, it can deteriorate during the pouring of the molten metal, potentially leading to defects in the casting
- **Environmental concerns:** Disposal of used sand can be an environmental concern, and the sand can sometimes contain harmful materials that require careful handling
- **Slow production rate:** Sand casting generally has a slower production rate compared to die casting or investment casting, making it less suitable for large-scale

Chapter 2.2: Investment casting

Casting processes

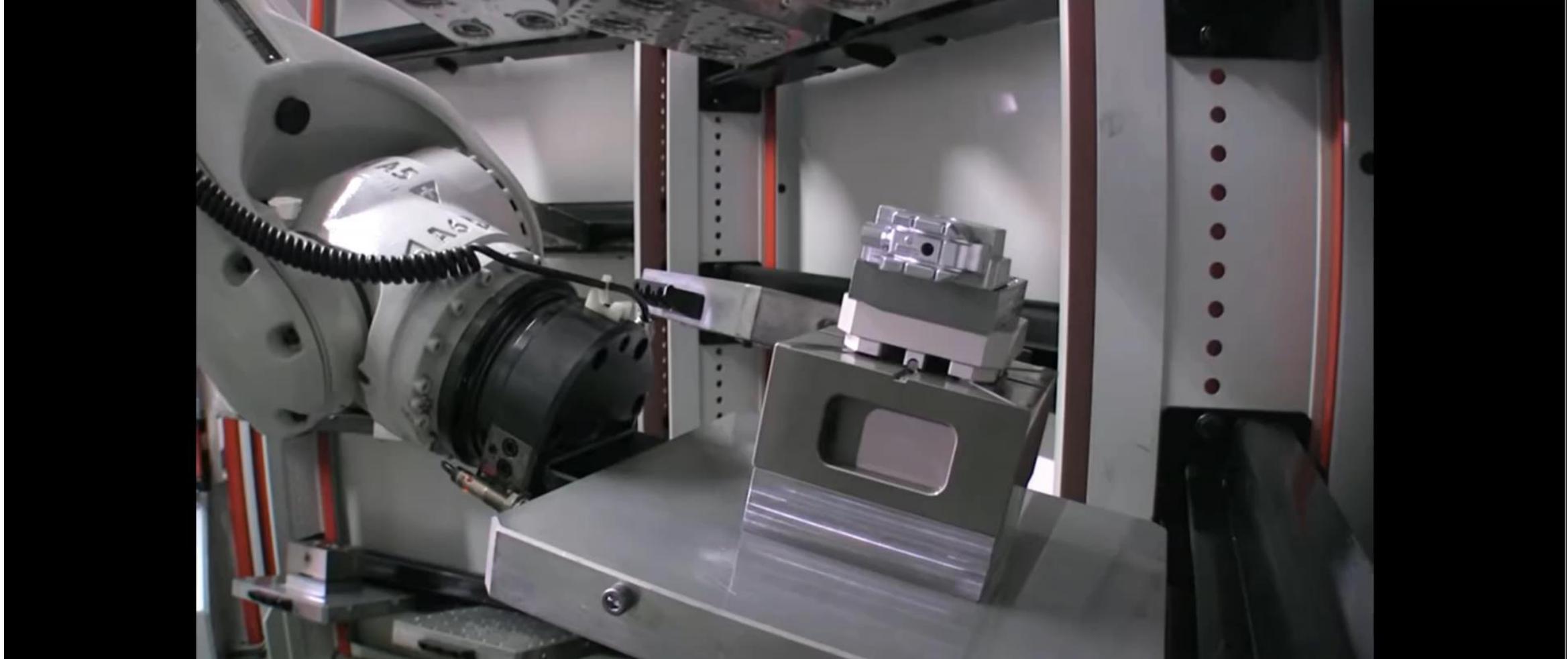
Process description



- **Wax Model Production:** Manufacturing of the wax model in a specially machined mold
- **Wax Model Assembly:** The wax model is usually manually assembled with other wax parts to form so-called wax trees.
- **Ceramic Dipping:** The assembled wax trees are dipped in a ceramic slurry and then coated with sand. This creates a ceramic shell around the wax, which serves as the casting mold
- **Burnout and Sintering:** Burning/melting out the wax trees from the ceramic shell and sintering the ceramic. This process creates the necessary mold stability
- **Casting:** The metal is poured into the still hot, wax-free mold
- **Cleaning and Separation:** Removal of the ceramic shell, separation of the supply channels, and completion of the casting parts

Casting processes

Process description



<https://www.youtube.com/watch?v=IFMVrHI8UwY>

Casting processes

Process description

Set of different investment casting parts

Source: PTZ Prototypen Zentrum GmbH



Prototypes of center consoles, 300 x 250 x 230 mm

Requirements: visible sides, as from die casting;
even joints between the screw parts

Alloy: AlSi10Mg

Source: Tübinger Stahlfeinguss;
Franz Stadtler GmbH & Co. KG



Rear swing arm of a fun bike;
Competition to SLM 3D printing

Alloy: AlSi10 type

Source: Tübinger Stahlfeinguss;
Franz Stadtler GmbH & Co. KG

Advantages

- + **High dimensional accuracy:** Investment casting can produce components with exceptional accuracy and intricate detail
- + **Excellent surface finish:** The process typically yields a smooth finish, reducing the need for post-casting machining
- + **Complex geometries:** It can create complex parts with undercuts, hollows, and intricate internal features that would be challenging with other methods
- + **Versatile material selection:** Investment casting is compatible with a wide range of metals, from steel and aluminum to superalloys.
- + **Precise casting with thin walls:** Allows for the production of parts with thin walls and high precision, which is difficult to achieve with other casting techniques
- + **Reduced waste and machining:** Produces near-net-shape parts that minimize waste and reduce the need for secondary machining operations

Disadvantages

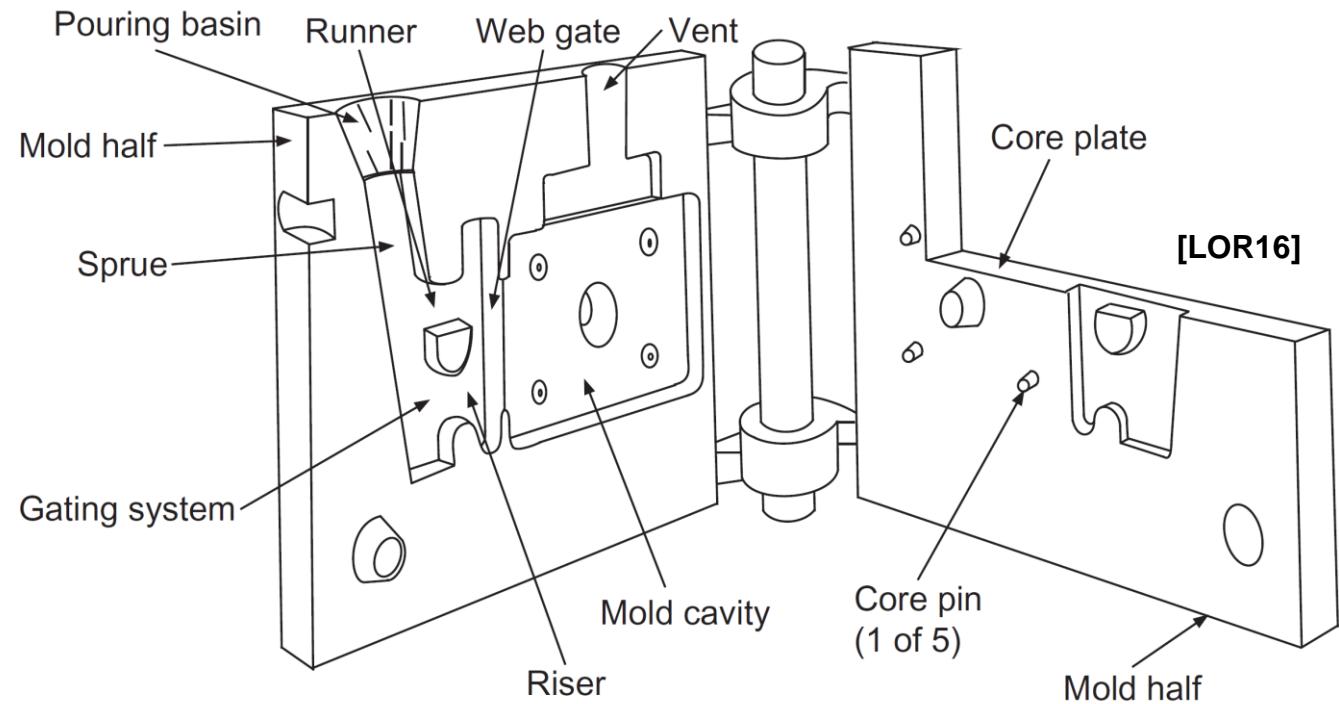
- **Higher cost for low volumes:** The process can be more expensive than other casting methods, especially for small production runs, due to the cost of materials and labor
- **Longer production cycles:** The multiple steps involved, such as creating the wax patterns and ceramic molds, can lead to longer lead times
- **Size limitations:** There are practical limits to the size and weight of components that can be economically produced through investment casting
- **Material limitations:** Not all materials can be cast with the same level of detail or dimensional accuracy
- **Potential for defects:** Issues such as ceramic shell cracking can lead to defects in the final product
- **Complex process control:** Requires tight control over numerous variables, from wax pattern production to mold creation and pouring, which can affect consistency and yield

Chapter 2.3: Permanent mold casting

Casting processes

Process description

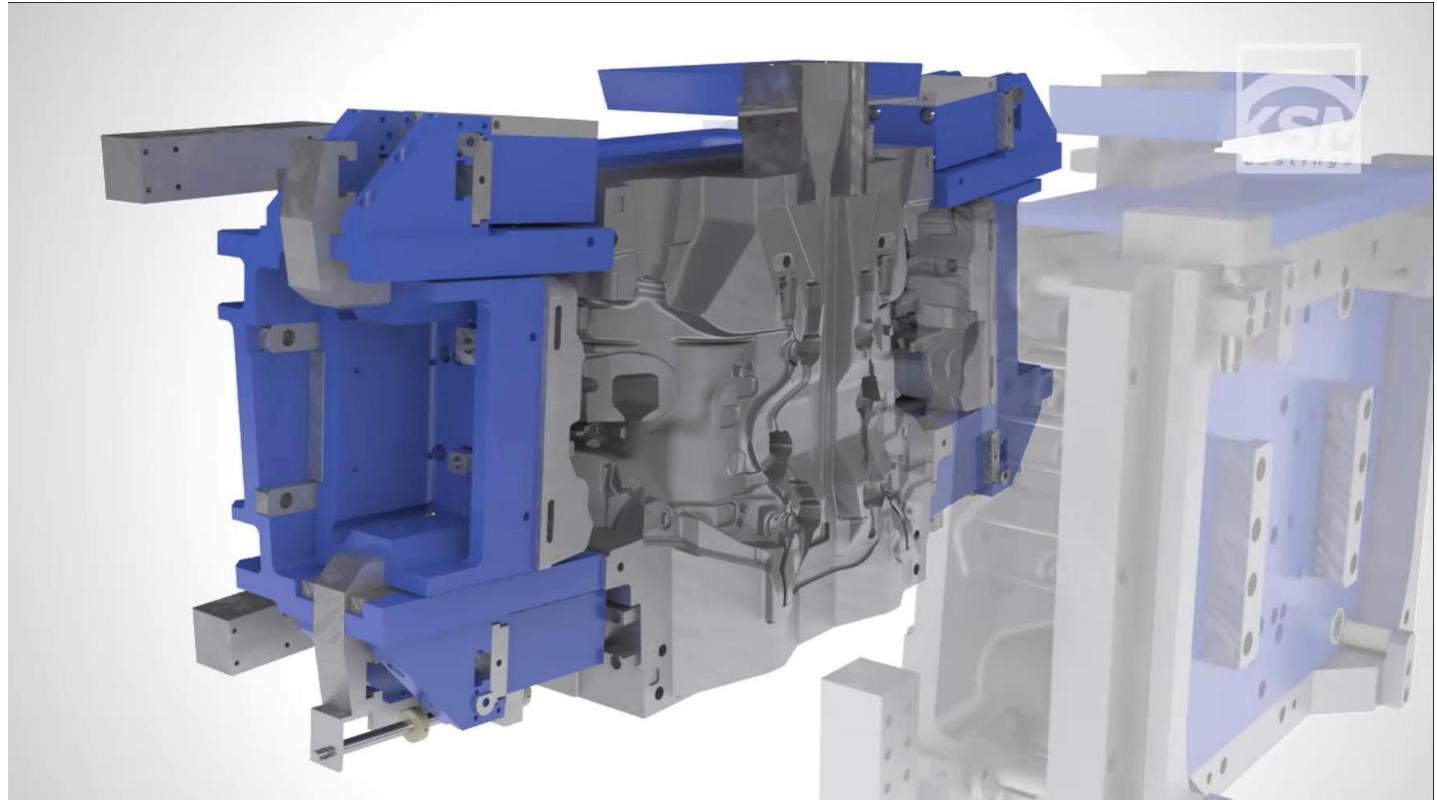
- Permanent mold casting uses durable, high thermal conductivity **molds**, unlike the single-use molds in sand casting
- Molds are typically made from materials, usually **hot work tool steels**, and are often referred to as "dies"
- **Interior surfaces are coated** to prevent adhesion and facilitate part removal
- Unlike sand molds, **permanent molds** are not destroyed during part extraction
- **Mold designs include "draft" angles** on internal surfaces to allow the removal of solidified metal parts



Sketch of a simple permanent mold casting tool and designation of the essential functional elements

Process description

- **Metal or ceramic cores** are used, considering the mold's ability to open and close
- Permanent molds are created through machining and **require vents** due to non-permeable materials
- **Ejector pins** may be present to assist in part removal
- **Higher thermal conductivity of the molds** leads to increased heat transfer rates and shorter solidification times
- **Heat conduction through the metal casting, not the mold, limits the solidification rate,** assuming constant temperatures for the metal melt and the mold

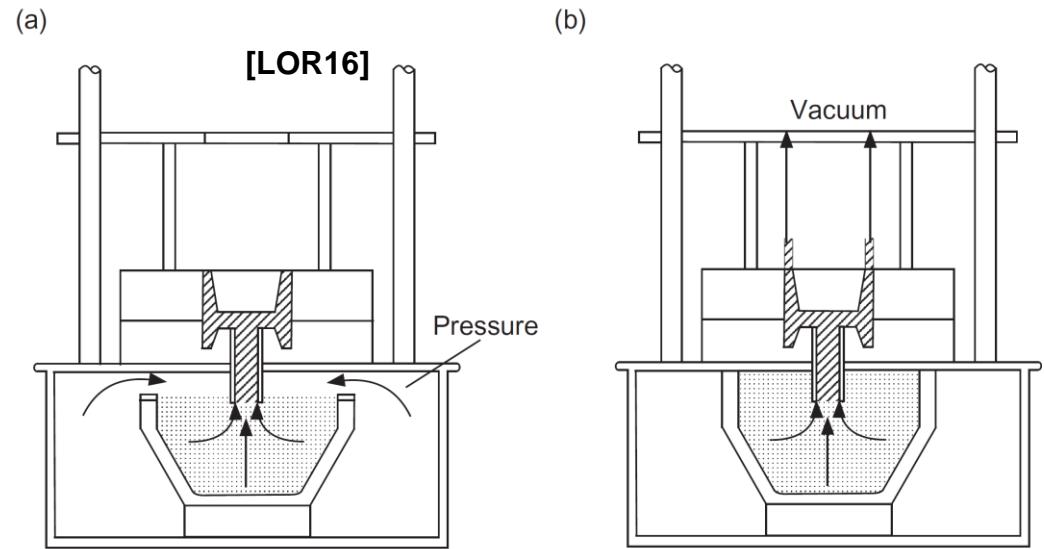


Animation of a permanent mold casting process
Source: KSM Castings Group GmbH

Casting processes

Different methods of metal dosing

- **Gravitational Pouring:** Utilizes gravity to fill the mold; the simplest and most common method
- **Vacuum Casting:** Uses a vacuum to draw molten metal into the mold; beneficial for reducing turbulence and entrapped gases.
- **(Low-)Pressure Casting:** Applies pressure to push the metal into the mold, allowing for faster filling and finer detail capture
- **Tilt Pouring:** Involves tilting the mold to gradually fill it, minimizing turbulence and air entrapment
- **Electromagnetic Pump:** Employs electromagnetic fields to control metal flow without direct contact, providing high precision and cleanliness.
- **Automated Ladle Systems:** Offers precise control over the volume and rate of metal poured into the mold, improving consistency and reducing waste



Sketch of a pressure (a) and vacuum (b) assisted permanent mold casting process

Casting processes

Some parts manufactured using the permanent mold casting process



Coated mold for the production of an aluminum alloy rim; casting process: low pressure permanent mold casting

Source: AEZ Wheels, ALCAR WHEELS GMBH



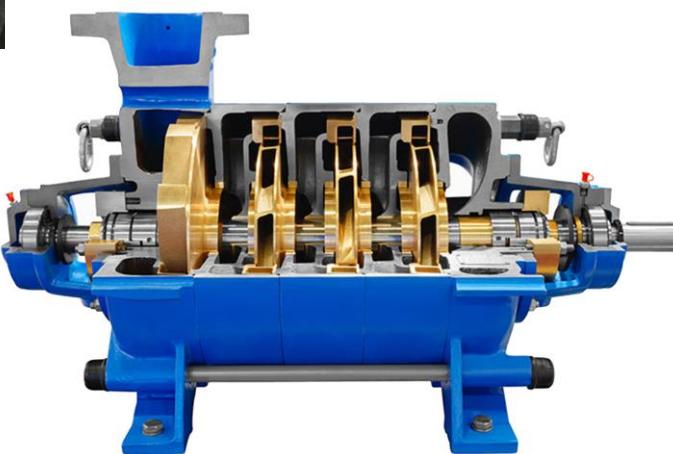
Aluminum permanent mold casting



Brass mold casting

For valve bodies of all types with different wall thicknesses

Sources: Walter Wagener GmbH



Pumps and underwater technology; achievement of high corrosion resistance, even in aggressive gaseous and liquid media

Source: MKB Metallguss Pumpen- und Unterwassertechnik

Advantages:

- + Suited for high volume production runs
- + Yields superior surface finish compared to sand casting
- + Offers better microstructure and dimensional accuracy
- + Rapid solidification results in fine microstructures, enhancing material properties

Disadvantages:

- High initial cost for mold creation, influenced by complexity and size
- Mold cost must be offset by the volume of units produced
- Size limitation for cast parts, usually no more than 50 kg
- Shape limitations due to parting lines of mold halves
- Generally limited to non-ferrous alloy casting

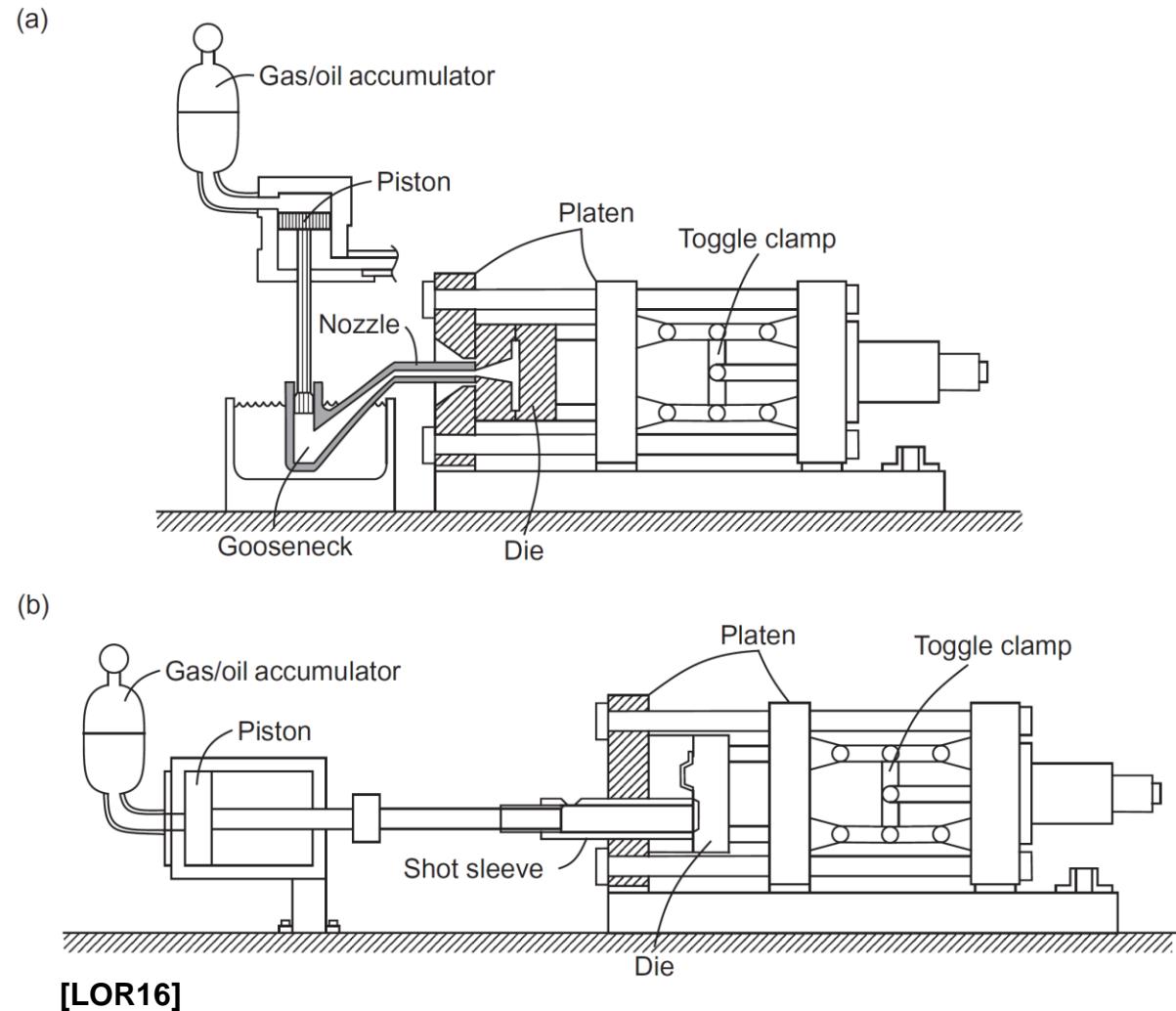
Chapter 2.4: High pressure die casting

Process description

- Die casting uses permanent metal molds, or "dies," with high-pressure metal injection
- Compensates for shrinkage via **pressurized melt feed**, not risers
- Limited to lower melting point, **nonferrous alloys** such as aluminum, magnesium, copper, and zinc

Die Casting Process Types:

- **Hot Chamber Die Casting (a):** Features an integrated melt reservoir and gooseneck system for metal injection.
- **Cold Chamber Die Casting (b):** Utilizes a separate furnace and automated ladle to transfer melt to the die, suited for higher temperature alloys.

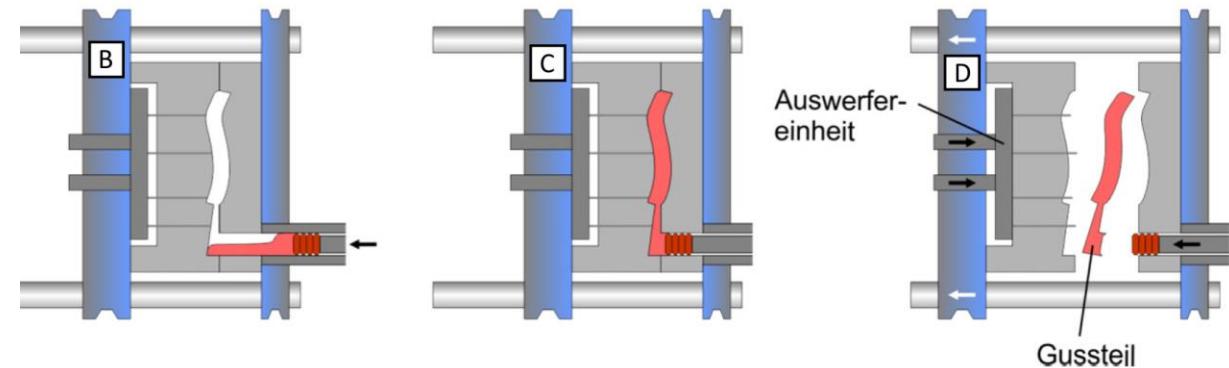
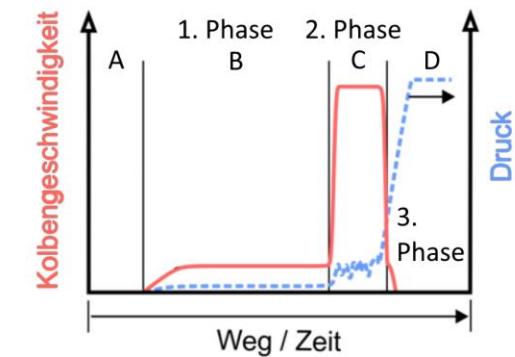
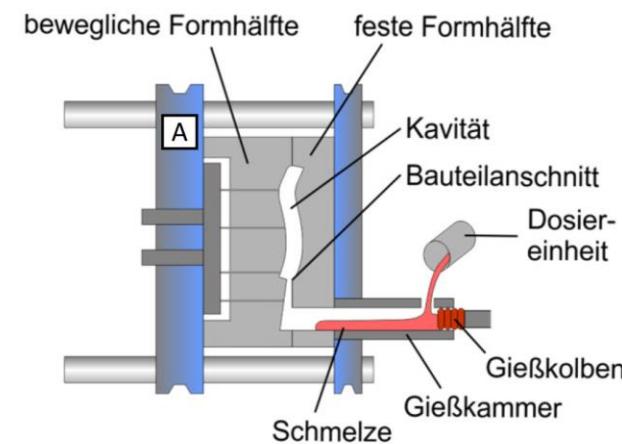


Process description

- Dies are made from high strength alloy steel and consist of at least two halves
- Mold cavities are filled through a series of sprues, runners, and gates
- Vents and cores are designed within the dies for air escape and internal features
- Mold temperature controlled by coolant channels, with an ejection mechanism included

Die Casting Steps and Pressures

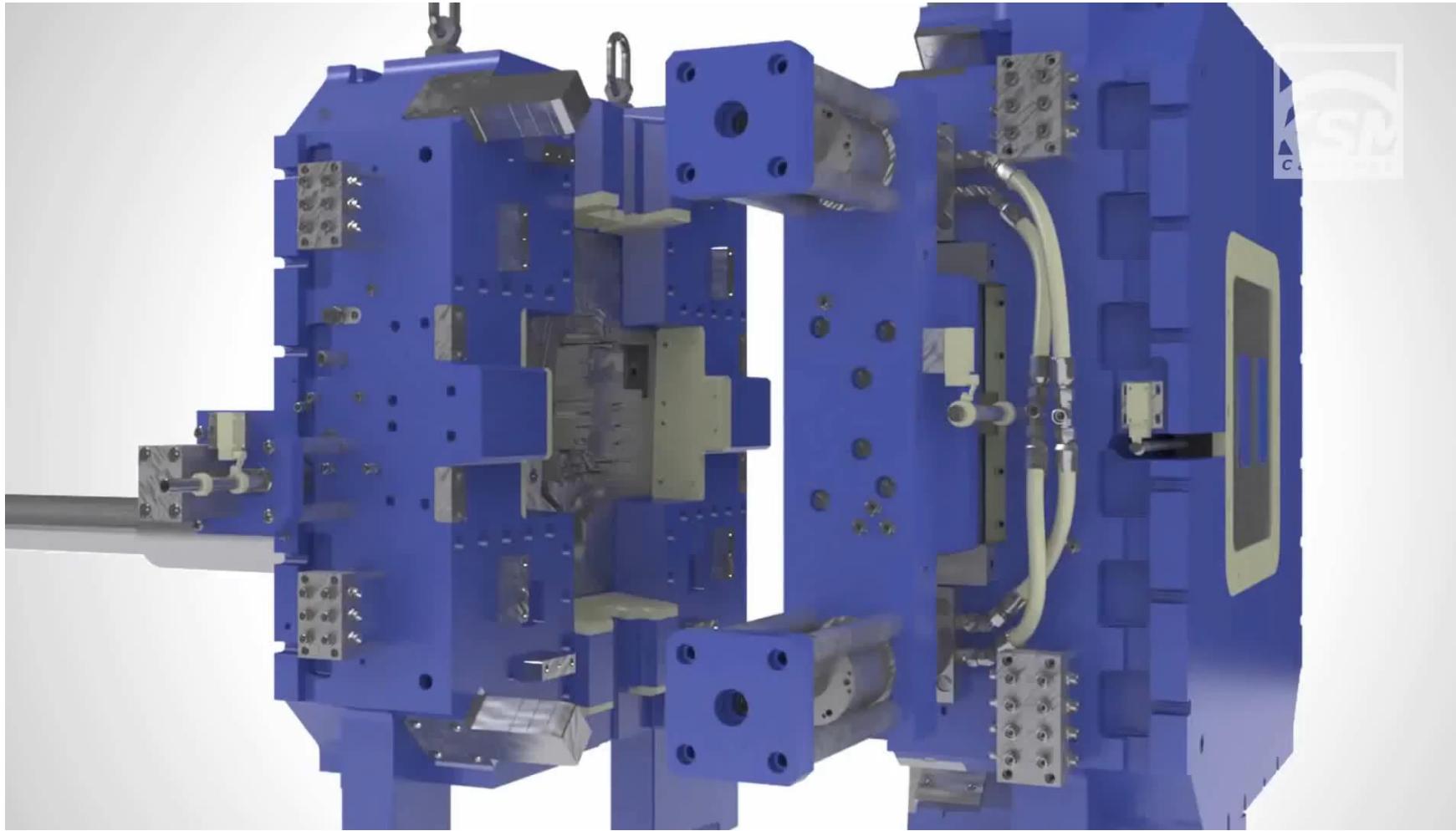
- Involves preparing the shot, coating and clamping the mold, controlled injection, solidification and part ejection
- Rapid injection speeds up to 80 m/s can introduce air and oxides
- Pressures up to 200 MPa are used, requiring substantial clamping forces based on the projected area of the mold
- Die casting machines are rated by clamping force, ranging from 450 kN to 100 MN, catering to various part sizes.



[SCH17]

Casting processes

Process description



Animation of a cold
chamber high pressure
die casting process

Source: KSM Castings
Group GmbH

Process description

The pressure die casting process consists of three phases:

Phase 1: Preliminary Phase/Chamber Filling

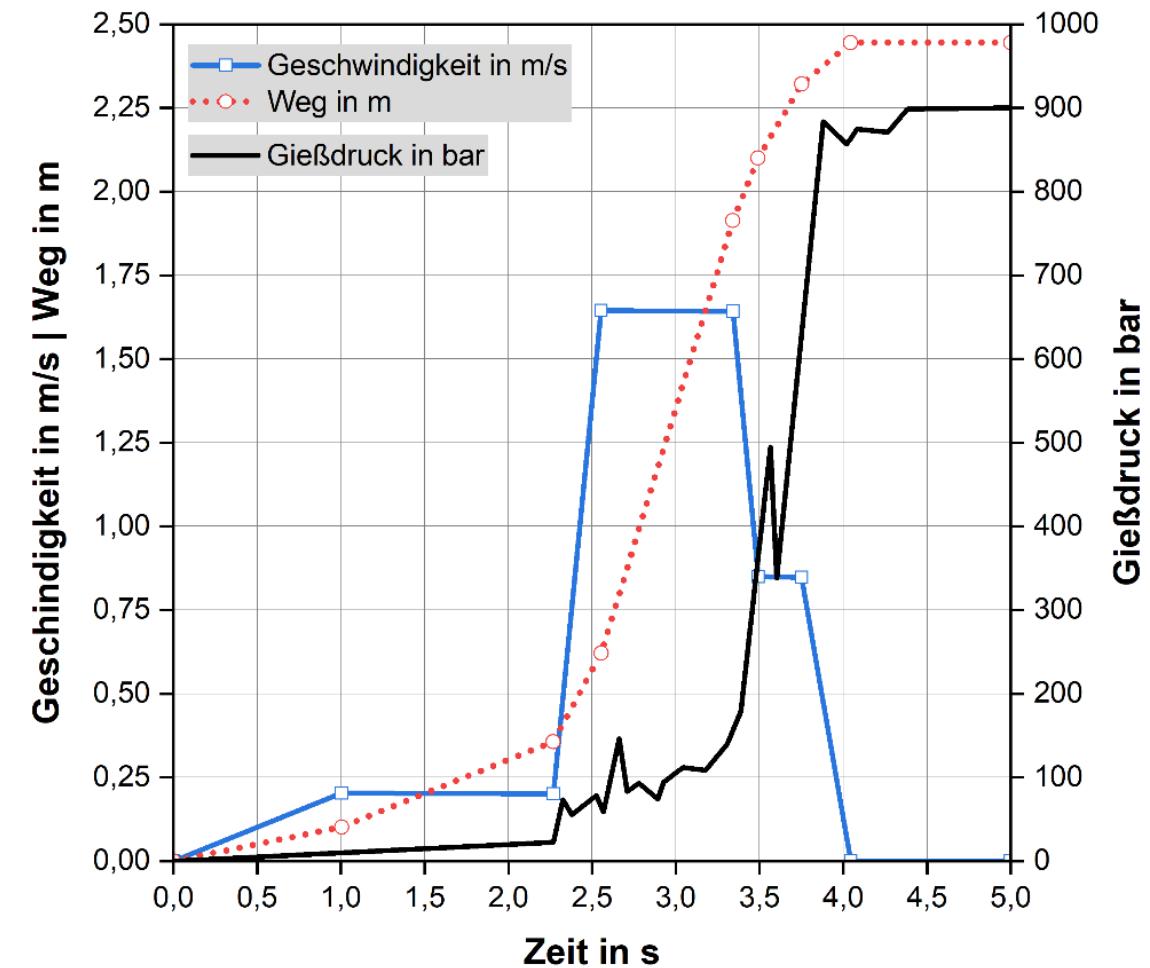
The casting piston is slowly moved towards the tool cavity, and the melt is backed up in the casting chamber

Phase 2: Mold Filling

The casting piston is rapidly accelerated forward, and the mold is completely filled in the shortest possible time

Phase 3: Pressurization

A slight movement of the casting piston within the tool cavity increases the pressure to counteract the shrinkage of the melt



Casting processes

Fast solidification in die casting processes

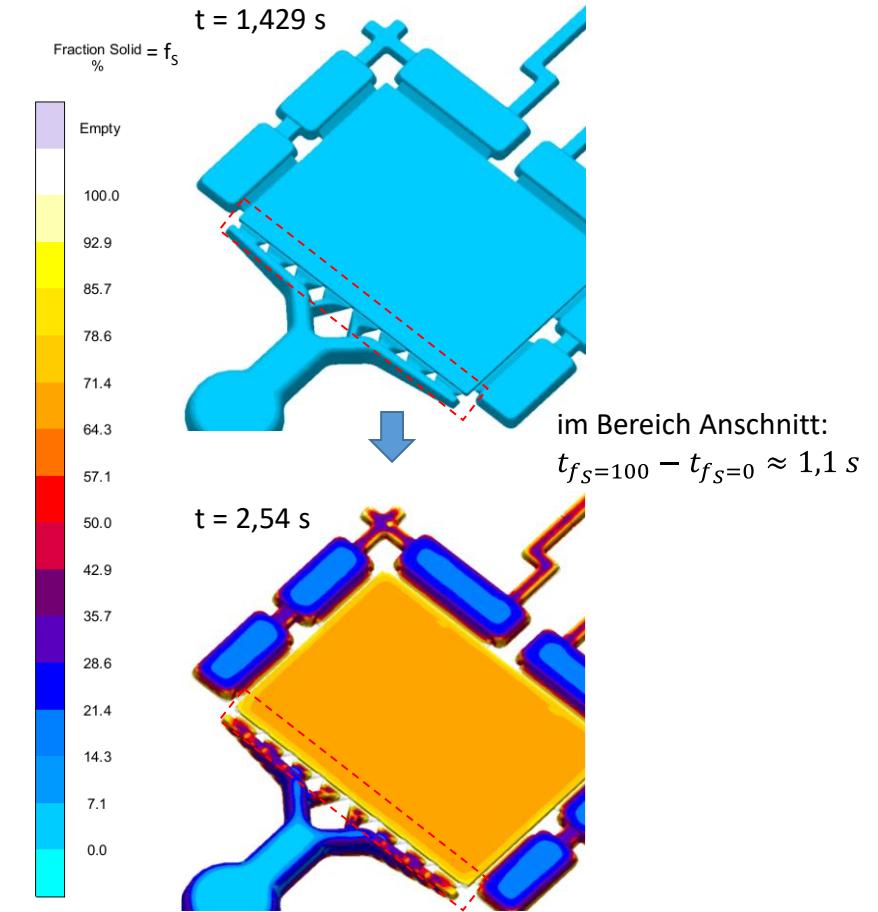
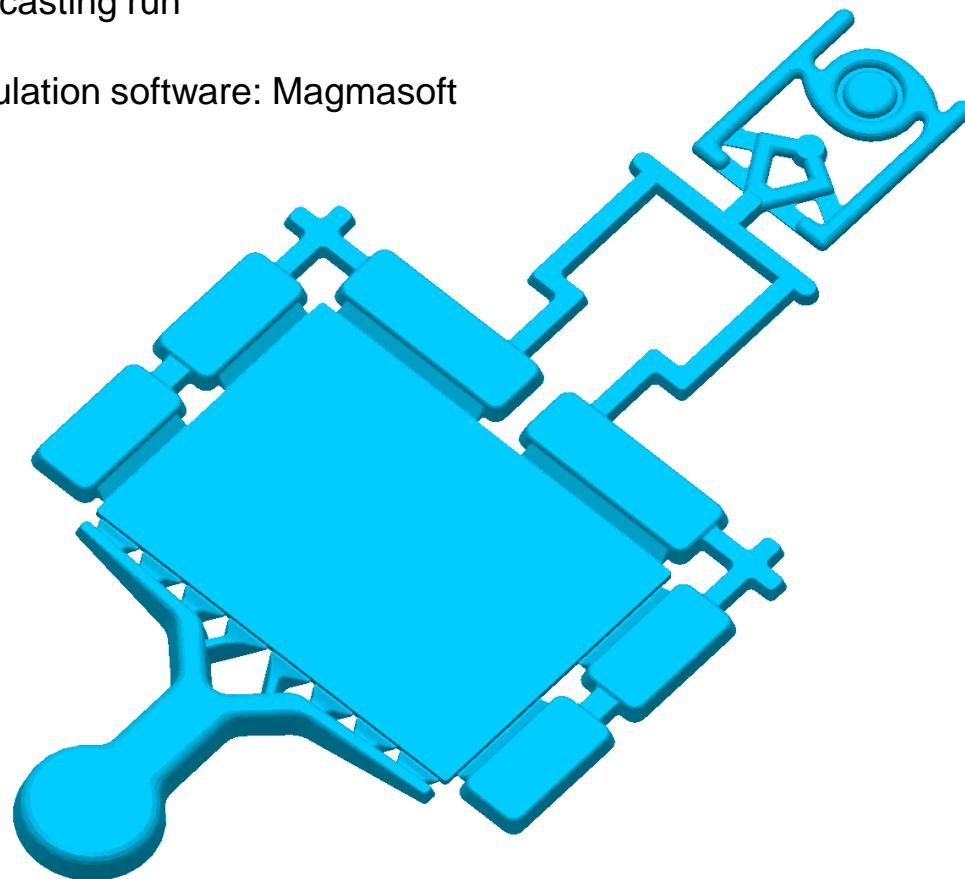
Simulation of the solid content during the solidification of a 3 mm plate incl. casting run

Casting process simulation software: Magmasoft

Real-time animation

$t = 1,429 \text{ s}$ bis

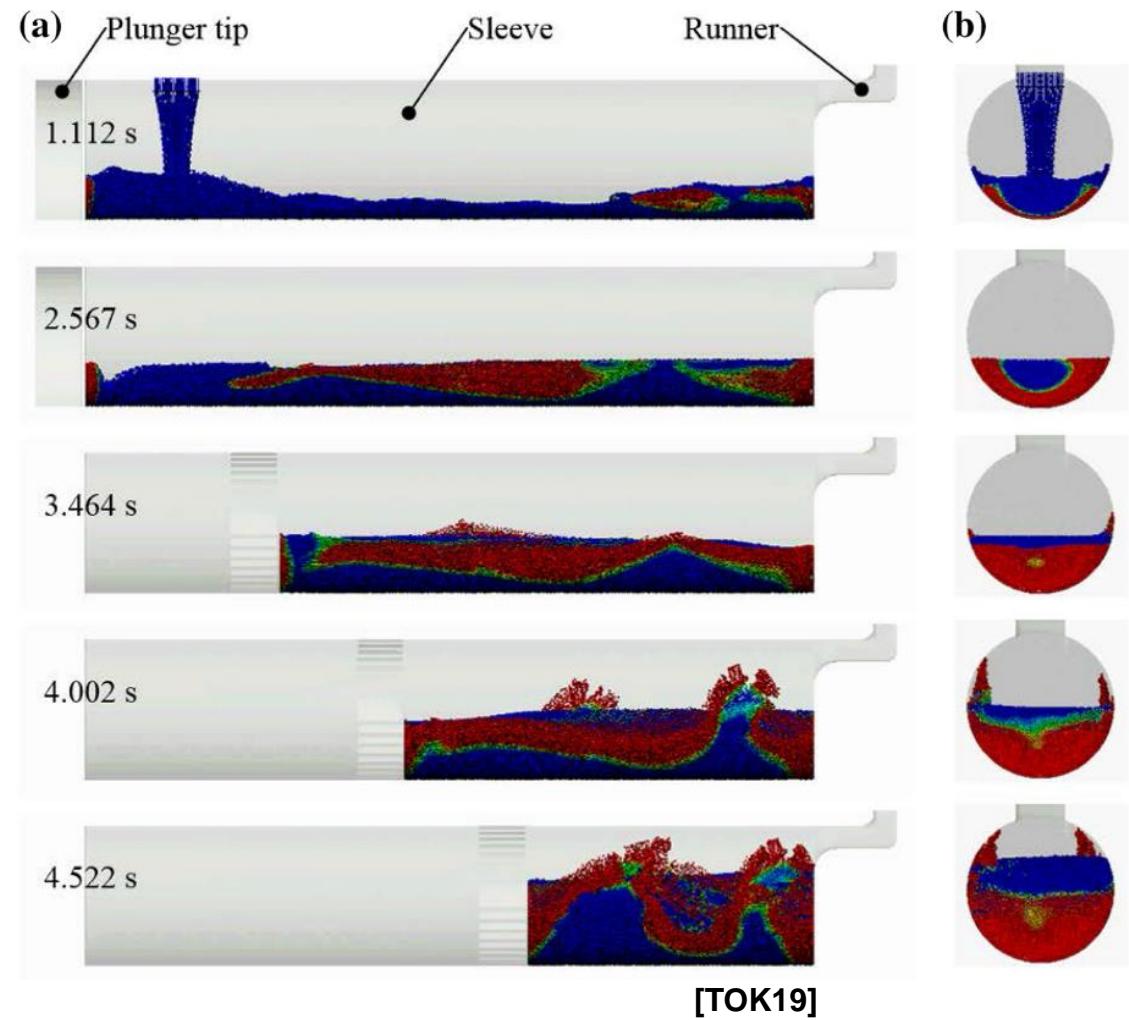
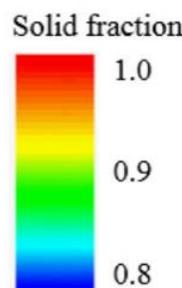
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Casting processes

Characteristic filling properties in the casting chamber

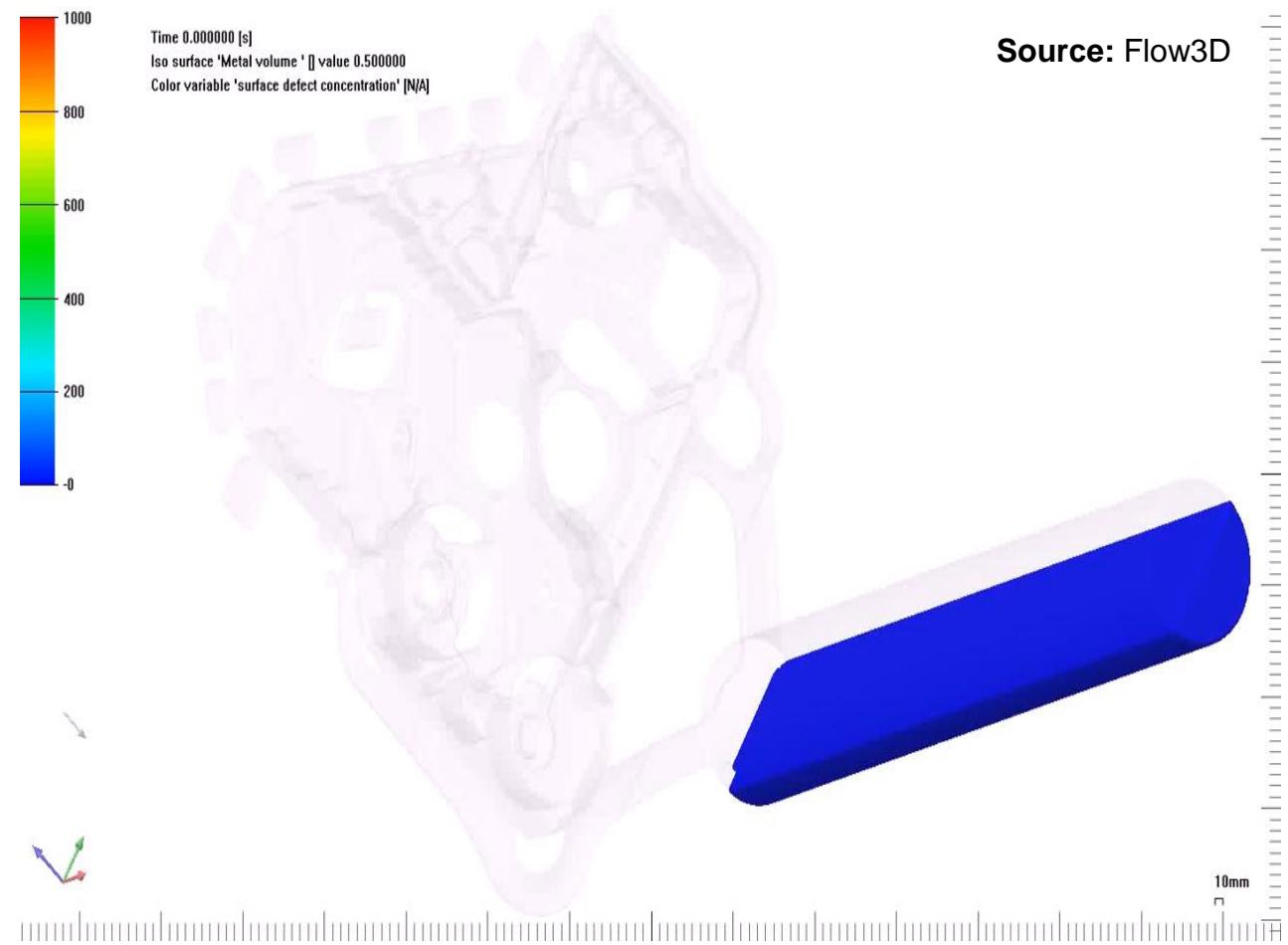
- Due to the high temperature difference between the chamber wall and the melt, solidification processes (pre-solidification) occur in the casting chamber
- These pre-solidified areas cause disturbances in the melt flow and bonding errors during mold filling, leading to dynamic differences from the melt → quality defects
- Solution:
 - Adjusting process control for consistent temperature and flow.
 - Using near-eutectic alloys to minimize solidification range



Casting processes

Characteristic filling properties in the cavity

- Metal melts possess a very high flow dynamic, i.e., highly unstable flow conditions (atomization, etc.)
- In contrast to plastic melts, the surfaces (flow fronts) of metal melts are significantly more **unstable** or **volatile**
- The fluid dynamic design of the casting system, as well as the casting parameters (e.g., mold filling speeds), are therefore of high importance, as they can cause unstable flow fronts, air entrapment, etc.
- Unstable flow fronts in metal casting are often due to the **high fluidity and temperatures involved**, necessitating precise control over the casting parameters to ensure quality
- Techniques like **computer simulation of fluid dynamics** are often employed to predict and mitigate these issues before actual production



Necessity of mold evacuation

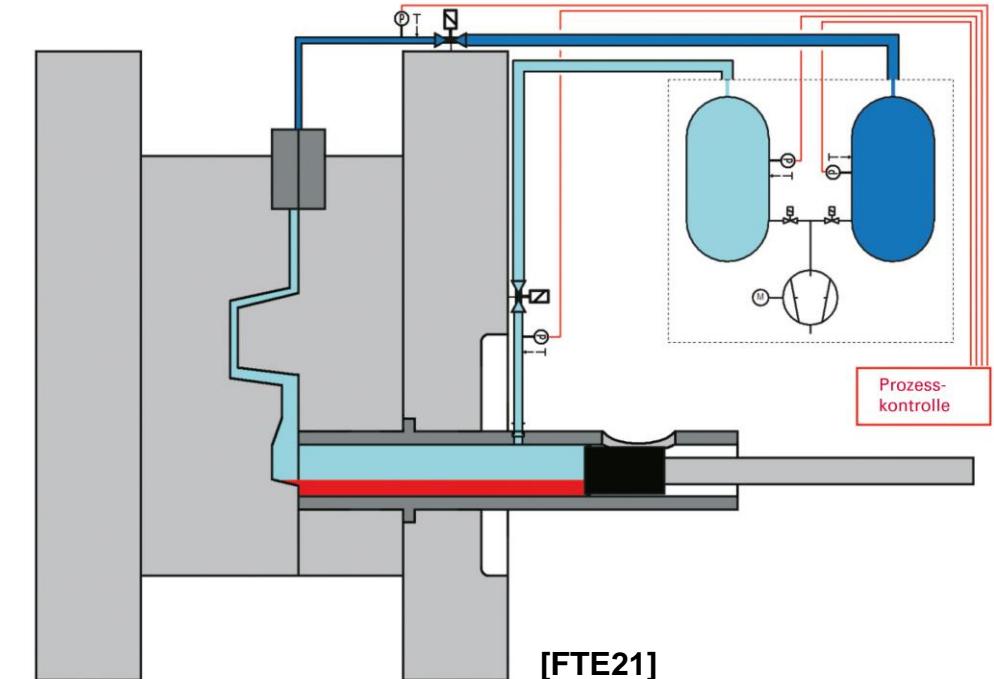
- Increasing demands on casting part quality regarding tightness and absence of porosity
- **Goal:** Prevention of filling-related gas pores during mold filling
- **Solution:** Vacuum-supported casting processes
- **Required:** Vacuum system as well as vacuum valves on the tool

Possible tool inserts with the function of a vacuum valve:

Valve-controlled

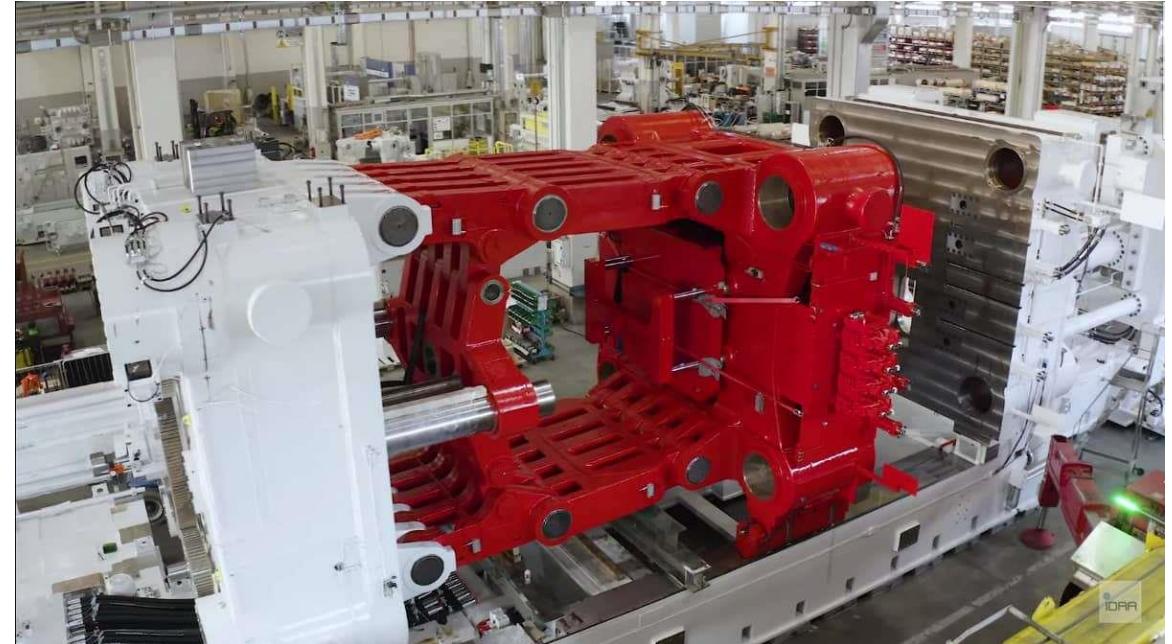
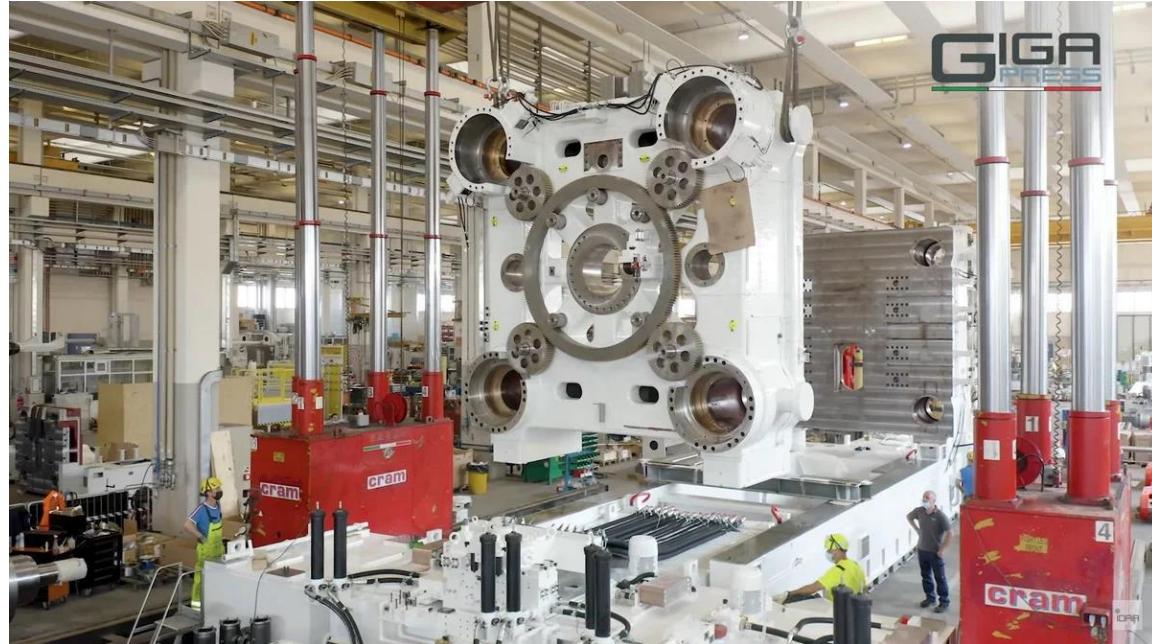


„metal freeezing“ / „Chillvents“



Casting processes

Views of a Giga-Casting die casting machine



Source: IDRA

- Tesla's Giga Press program features aluminum die casting machines made by IDRA Group in Italy
- As of 2020, IDRA presses were the largest in production, with clamping forces between 55,000 and 61,000 kilonewtons
- The machines themselves weigh between 410 and 430 tons
- Injection of 80 kilograms of molten aluminum into molds at a speed of 10 meters per second
- Cycle time of approximately 80 to 90 seconds → output rate is about 40-45 castings per hour, equating to roughly 1,000 castings daily

Advantages:

- + High production rate suitable for mass production
- + Excellent dimensional accuracy for precision components
- + Smooth surface finish reduces the need for post-processing
- + Near net shape casting minimizes required machining

Disadvantages:

- Requires steel molds, which are expensive and limit the size of the cast part
- Limited to certain alloys, typically non-ferrous
- Design is constrained to thin-walled sections, similar to polymer injection molding

Casting Method	Characteristics	Advantages	Disadvantages
Sand Casting	<ul style="list-style-type: none">Non-permanent mold; uses sand-based molds	<ul style="list-style-type: none">Low-cost toolingVersatile alloy selectionLarge parts possible	<ul style="list-style-type: none">Rough surface finishLess precise dimensional control
Investment Casting	<ul style="list-style-type: none">Uses a ceramic mold created around a wax pattern	<ul style="list-style-type: none">Excellent surface finishHigh dimensional accuracyWorks with a wide range of alloys	<ul style="list-style-type: none">Higher cost of toolingLonger production cycles
Permanent Mold Casting	<ul style="list-style-type: none">Reusable molds; typically made of metal	<ul style="list-style-type: none">Good for medium to high volume productionBetter surface finish than sand castingFaster solidification	<ul style="list-style-type: none">Higher initial tooling costsLimited to non-ferrous alloys
High-Pressure Die Casting	<ul style="list-style-type: none">Metal mold under high pressure; rapid injection	<ul style="list-style-type: none">High production ratesExcellent dimensional accuracyGood surface finish	<ul style="list-style-type: none">High tooling costLimited to small, thin-walled partsRestricted to non-ferrous alloys

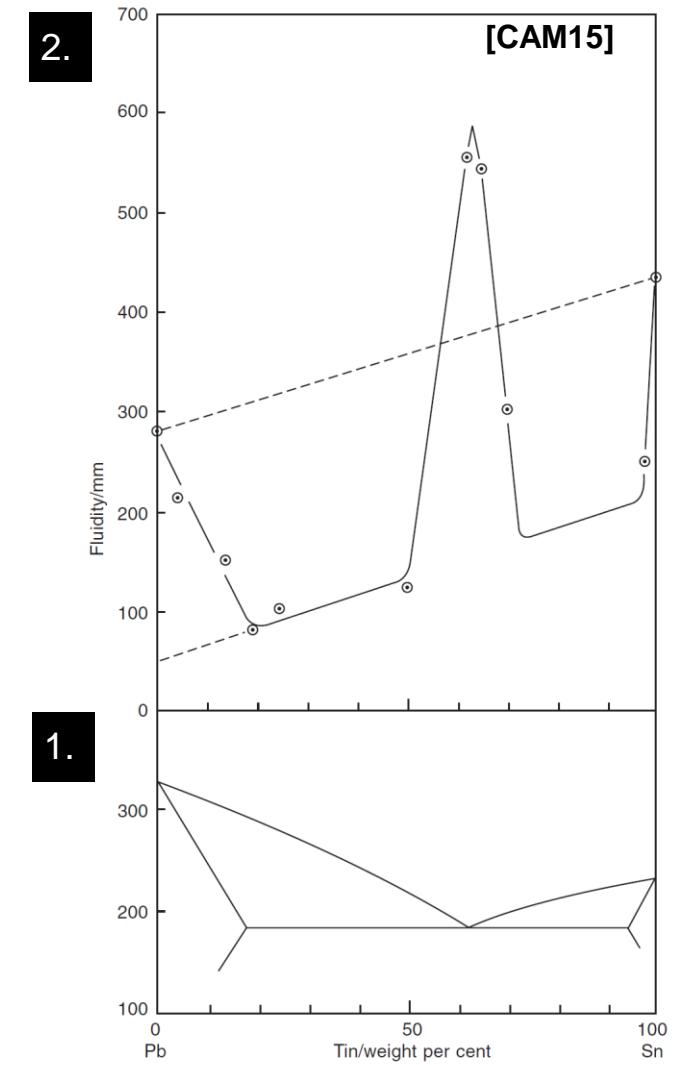
Chapter 3: Materials: alloys, melt treatment, heat treatment of cast components

Chapter 3.1: Definition of a castable alloy

Definition of a castable alloy

Key characteristics of castable alloys:

1. **Melting Point:** Manageable for industrial casting processes
2. **Fluidity:** High fluidity to fill intricate mold designs and thin sections
3. **Shrinkage & Solidification:** Predictable shrinkage; minimal to avoid defects
4. **Machinability:** Easily machinable post-casting for further processing
5. **Hot Tearing & Cracking Resistance:** Resilient against thermal stresses during cooling
6. **Chemical Stability:** Stable at high temperatures; non-reactive with mold or atmosphere
7. **Cost & Availability:** Economically viable and readily available
8. **Mechanical Properties:** Suitable strength, hardness, and ductility for intended use



Chapter 3.2: Shrinkage during solidification

Shrinkage during solidification

Definition: Shrinkage refers to the reduction in volume as a material transitions from liquid to solid during cooling.

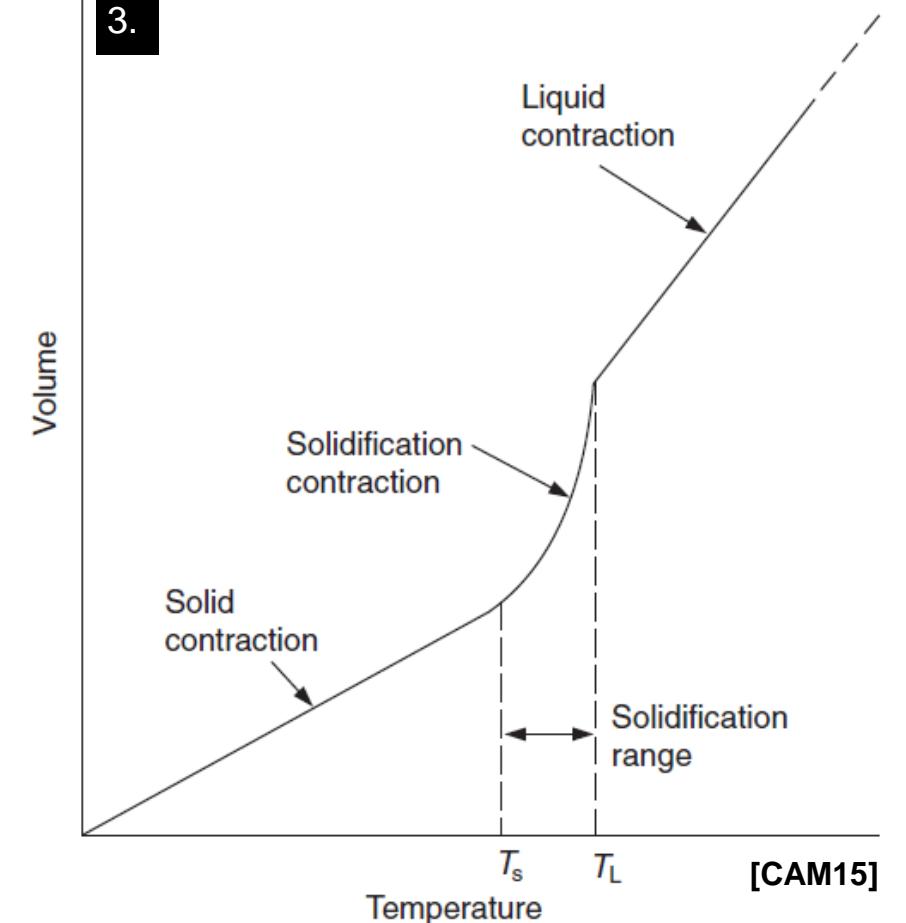
Types of Shrinkage/Contraction:

- **Liquid Shrinkage:** Occurs as the metal cools from pouring temperature to solidification temperature
- **Solidification Shrinkage:** Happens when the metal changes from liquid to solid phase
- **Solid Shrinkage:** The volume reduction during cooling of solid metal to room temperature

Implications:

- **Mold Design:** Molds must account for shrinkage to maintain dimensional accuracy
- **Risers:** Used to compensate for shrinkage by supplying additional liquid metal
- **Alloy Selection:** Different alloys exhibit different shrinkage rates
- **Defects!**

3.



Progression of the specific volume over the temperature

Table 7.1 Solidification Shrinkage for Some Metals

Metal	Crystal Structure	Melting Point °C	Liquid Density (kgm ⁻³)	Solid Density (kgm ⁻³)	Volume Change (%)	References
Al	fcc	660	2368	2550	7.14	1
Au	fcc	1063	17,380	18,280	5.47	1
Co	fcc	1495	7750	8180	5.26	1
Cu	fcc	1083	7938	8382	5.30	1
Ni	fcc	1453	7790	8210	5.11	1
Pb	fcc	327	10,665	11,020	3.22	1
Fe	bcc	1536	7035	7265	3.16	1
Li	bcc	181	528	—	2.74	4, 5
Na	bcc	97	927	—	2.6	4, 5
K	bcc	64	827	—	2.54	4, 5
Rb	bcc	303	11,200	—	2.2	2
Cd	hcp	321	7998	—	4.00	2
Mg	hcp	651	1590	1655	4.10	3
Zn	hcp	420	6577	—	4.08	2
Ce	bcc	787	6668	6646	-0.33	1
In	tetrag	156	7017	—	1.98	2
Sn	tetrag	232	6986	7166	2.51	1
Bi	rhomb	271	10,034	9701	-3.32	1
Sb	rhomb	631	6493	6535	0.64	1
Si	diamond	1410	2525	—	-2.9	2

fcc, face centered cubic; bcc, body centered cubic; hcp, hexagonal close packed; tetrag, tetragonal; rhomb, rhombic.

References: 1, Wray (1976); 2, Lucas (quoted by Wray, 1976); 3, This book; 4, Lida and Guthrie (1988); 5, Critical review by J. Campbell in Brandes (1983).

Key Concept: During solidification, liquids typically contract due to atomic rearrangement from a ‘random close-packed’ structure to a denser crystalline structure

Solid Density and Contraction:

- **Close-Packed Metals (fcc & hcp):** Exhibit the highest contraction on solidification, ranging from 3.2–7.2%
- **Less Close-Packed Metals (bcc):** Experience moderate solidification shrinkage between 2–3.2%
- **Other Materials:** Less dense solids may contract less or even expand upon freezing

Expansive Materials: Water, silicon, and bismuth are known to expand on freezing.

Cast Iron: An important alloy that also expands on solidification (graphite formation tends to occupy more volume than the liquid iron from which it precipitates; eutectic reaction)

fcc = face centered cubic

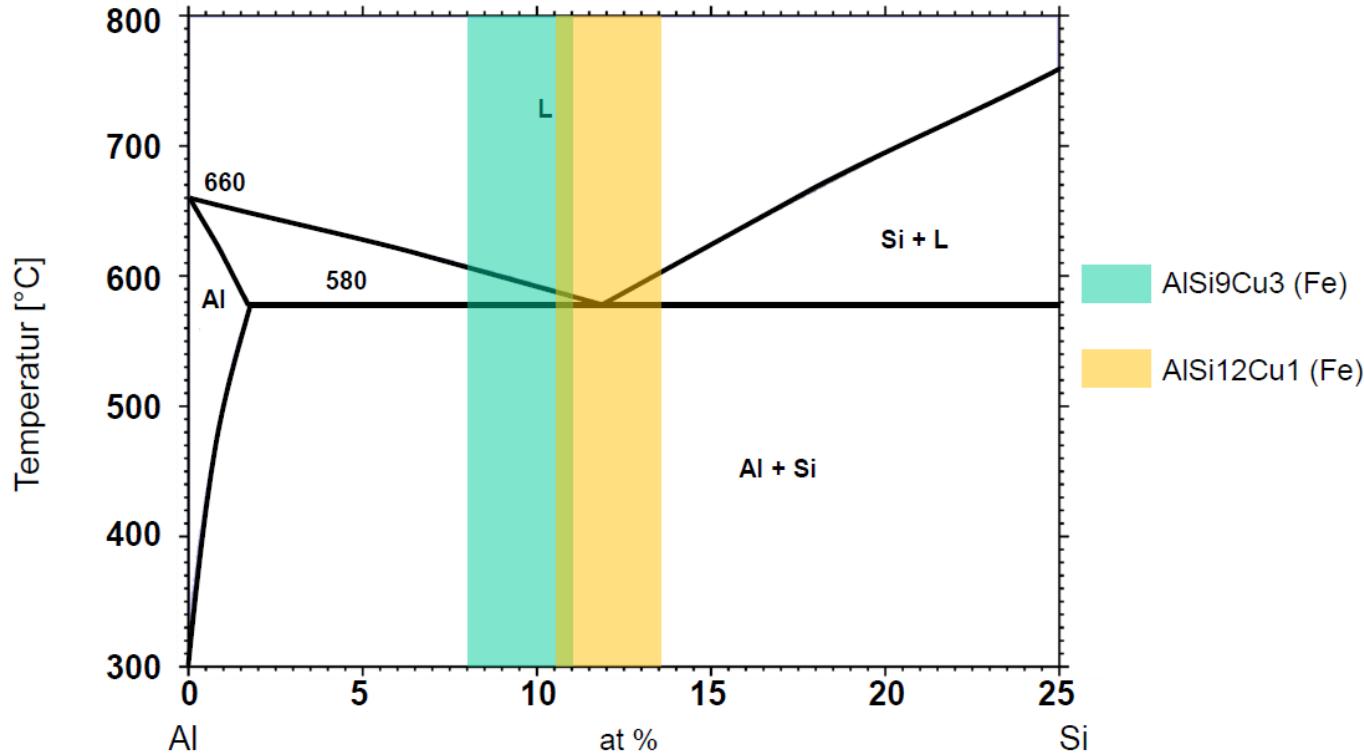
hex bzw. hcp = hexagonal close packed

bcc = body centered cubic

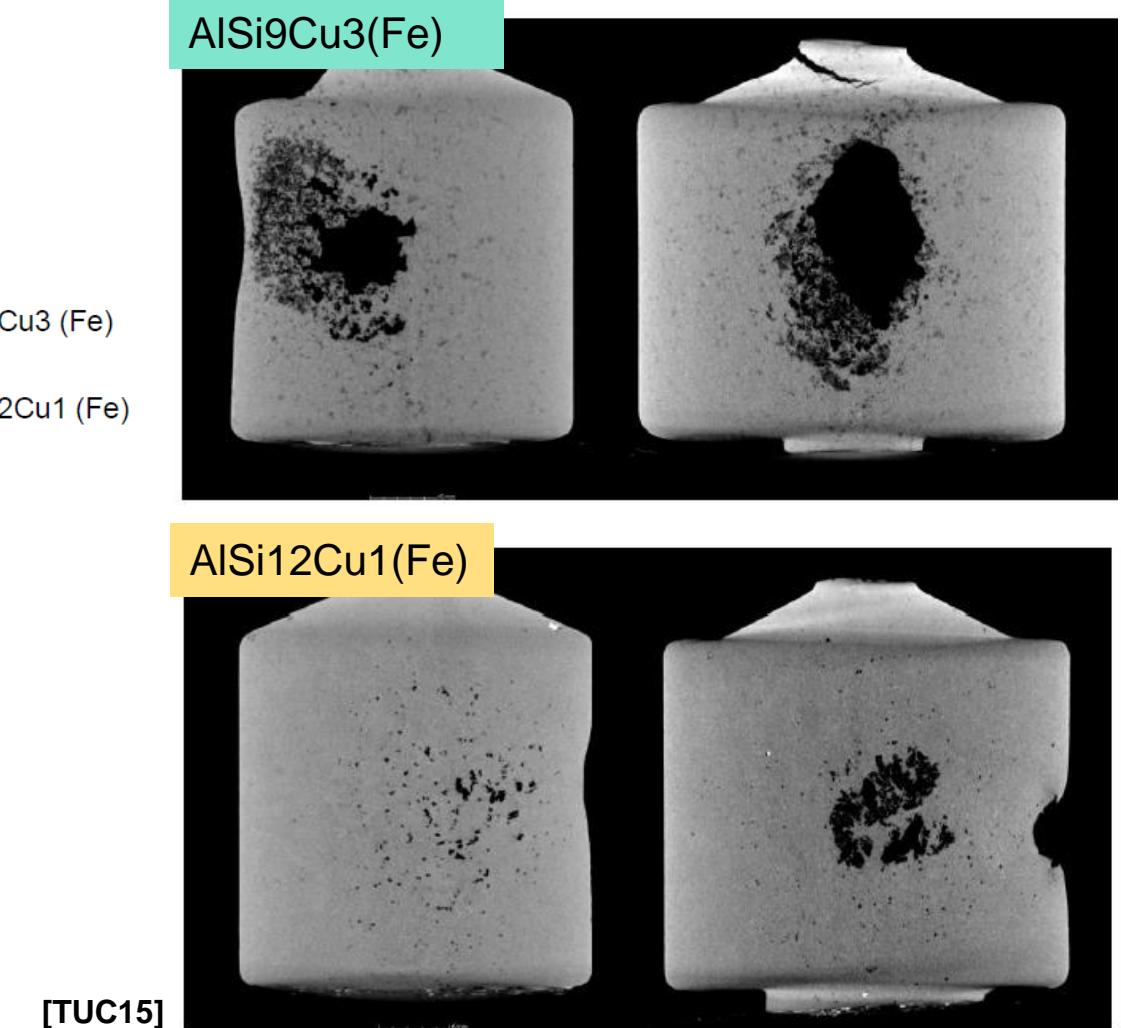
[CAM15]

Materials

Shrinkage during solidification – Graphical visualisation



- The solidification shrinkage depends on the solidification interval of the selected alloy
- Castability at the eutectic ↔ Solidification shrinkage



[TUC15]

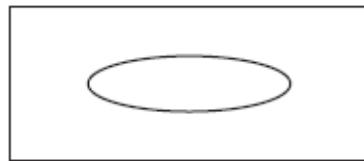
Feeding Mechanisms & Porosity:

- Pressure gradients drive feeding mechanisms, reducing porosity
- Feeding vs. pore formation depends on the **presence of nuclei**
- Clean metal without nuclei will continue feeding until fully solid, avoiding porosity

Shrinkage Porosity Consequences:

- Even small contractions in size can lead to significant internal cavities
- For most cast materials, shrinkage porosity is a major threat to integrity

(a) Effective internal pore nucleation



(b) Intermediate case

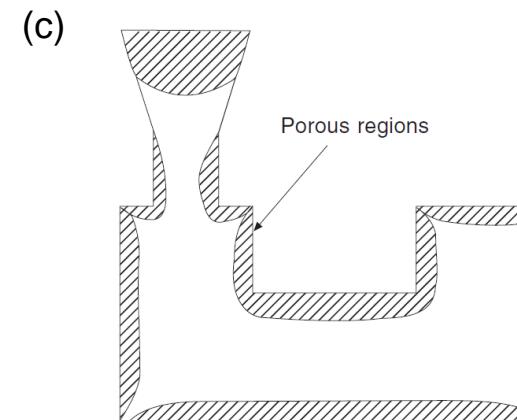
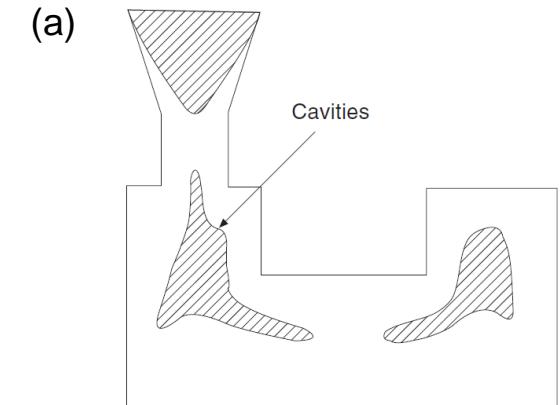


(c) No internal pore nucleation



[CAM15]

Three forms of shrinkage porosity: a) internal, b) mixed, c) external shrinkage porosity



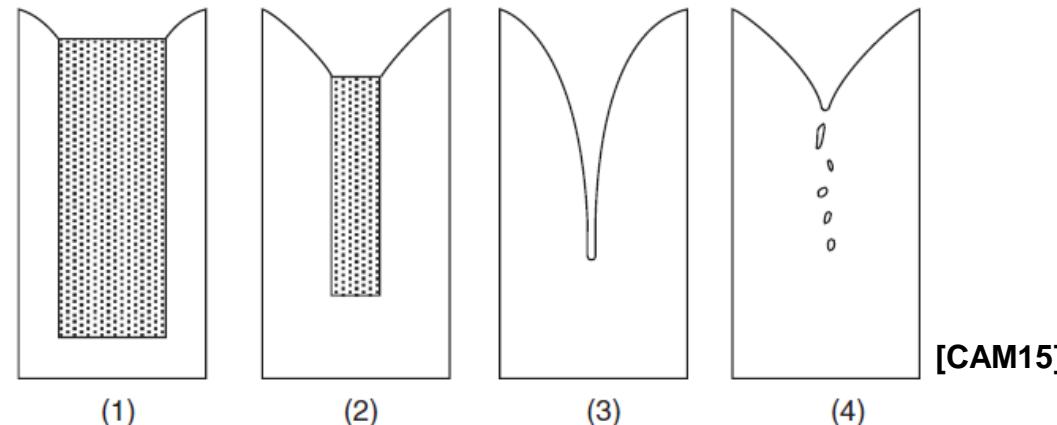
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Porosity Management:

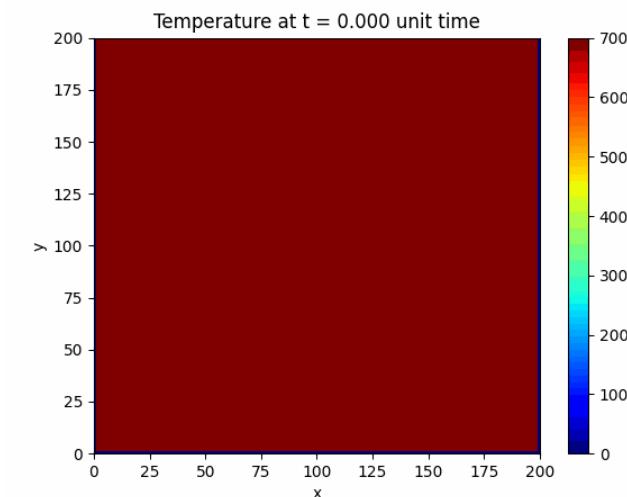
- Displacing internal porosity to the casting's exterior is a recommended strategy
- External porosity is less harmful and often unnoticeable, manageable by pattern adjustments

Prevention Strategies

- Improving metal cleanliness reduces porosity
- Designing for good feeding accommodates volume changes during freezing

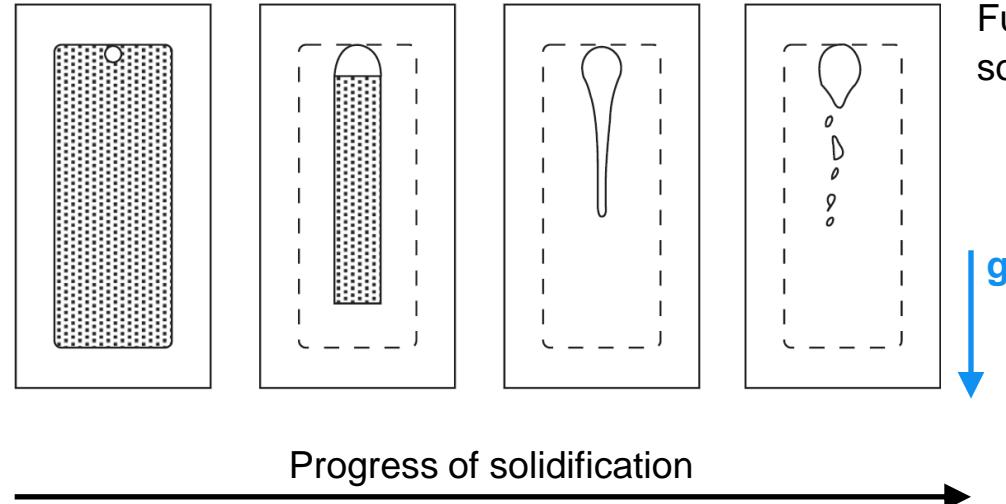


Stages in the development of a primary shrinkage pipe



Modelled temperature distribution of a shrinkage pipe

Shrinkage during solidification – Boundary conditions | Defect formation

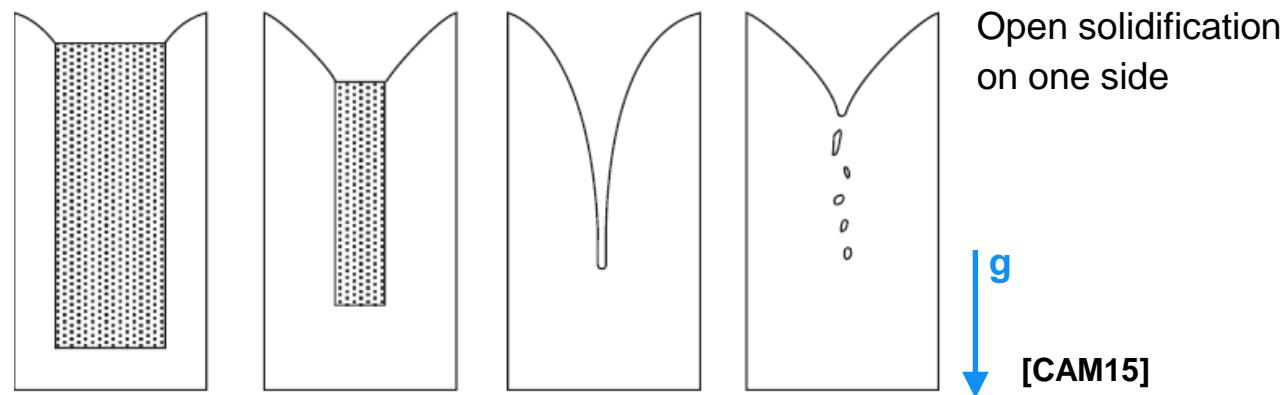


Fully enclosed solidification

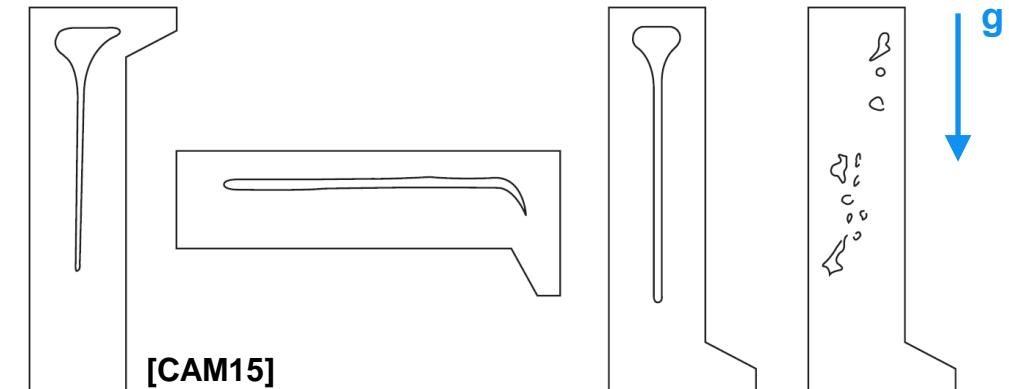
The effect formation depends on:

- Temperature distribution (component geometry, mold wall heat transfer, mold wall material)
- direction of gravity
- alloy concentration in the component
- presence of defect-forming nuclei

Understanding the behavior of shrinkage is crucial to casting integrity

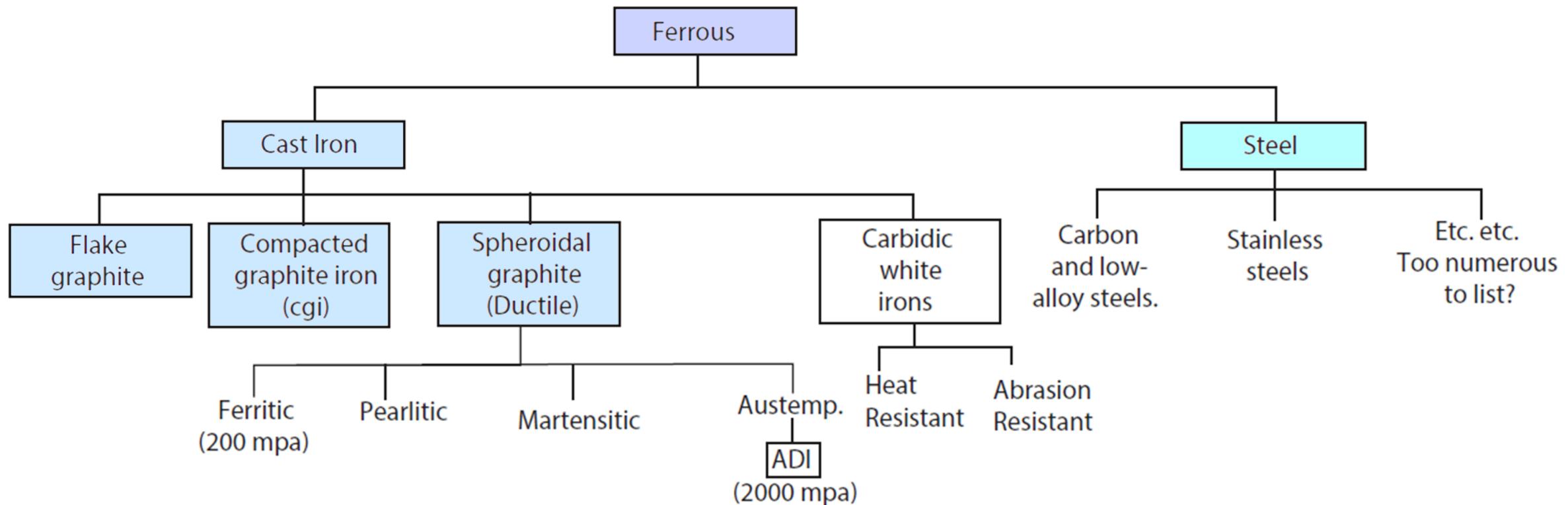


Open solidification on one side



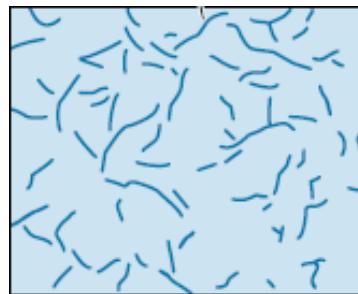
Chapter 3.3: Ferrous alloys

Ferrous alloys – Overview

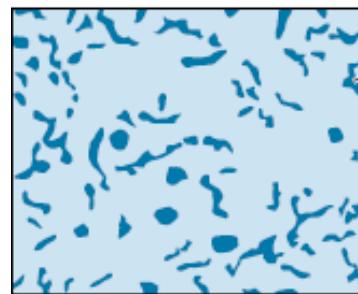


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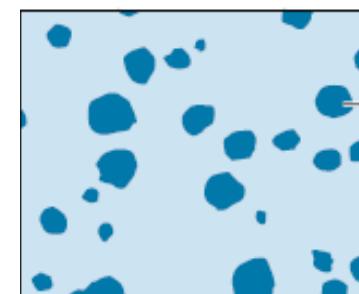
Type	Structure	Properties	Applications
Grey Cast Iron (Flake Graphite)	Flake-like graphite	Good machinability, vibration damping, wear resistance	Machine bases, automotive parts (engine blocks, brake drums), cookware
Compacted Graphite Iron (CGI)	Compacted, worm-like graphite	Balance of strength, ductility, thermal conductivity, damping; higher tensile strength than grey iron	Heavy-duty engine blocks, turbo housings, industrial applications
Ductile Cast Iron (Spheroidal Graphite)	Small, spherical graphite nodules	Excellent ductility, high impact strength, good fatigue resistance	Heavy machinery parts, automotive components (gears, suspension parts), water and sewer pipes



Grey Cast Iron



Compacted Graphite Iron



Ductile Cast Iron

Ferrous alloys – Cast Iron

Grey Iron (ASTM A48)

Composition: 2.5% - 4% Carbon, 1% - 3% Silicon, rest Iron; sometimes small amounts of manganese, phosphorus, and sulfur

German Convention: EN-GJL (previously DIN GG)

Example: EN-GJL-250 (similar to GG25)

The number after EN-GJL (or GG) represents the approximate minimum tensile strength in MPa

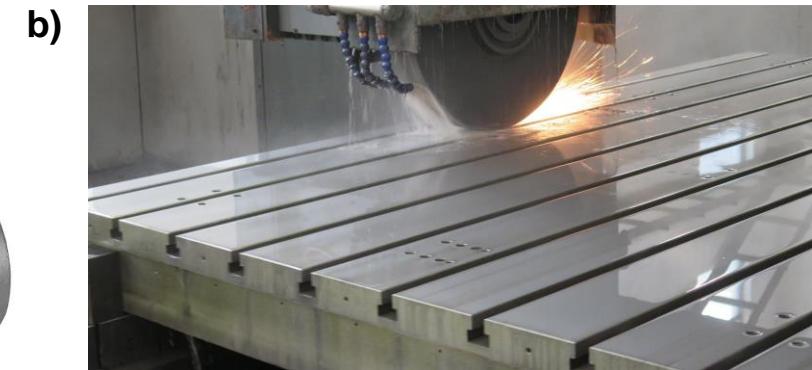
Ductile Iron (ASTM A536)

Composition: 3% - 4% Carbon, 2% - 3% Silicon, 0.3% - 0.4% Manganese, 0.03% - 0.04% Magnesium, rest Iron

German Convention: EN-GJS (previously DIN GGG)

Example: EN-GJS-400-15 (similar to GGG40)

The numbers denote minimum tensile strength and elongation; for example, 400-15 means 400 MPa tensile strength with 15% elongation



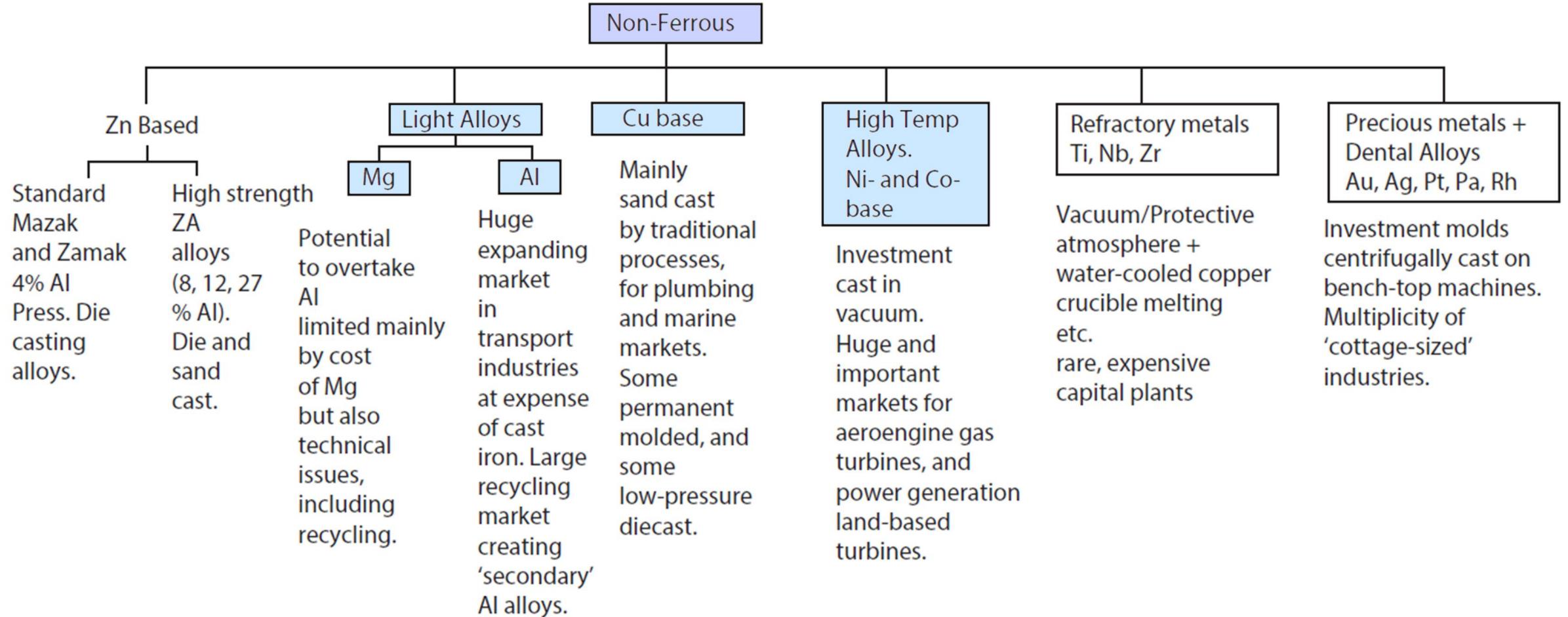
a)

- a) Shut-off valve, grey iron (GJL-250)
Source: Fromme Armaturen
- b) Cast iron machine plate, grey iron (GJL-350)
Source: SCHULTE Maschinenteile GmbH
- c) Transverse link, ductile iron (EN-GJS)
Source: HEUNISCH

Side information: "GJL" is an abbreviation where "G" stands for "Guss" (the German word for "cast"), "J" stands for "Iron," and "L" indicates that the graphite in the iron is in a flake (lamellar) form, which is characteristic of grey cast iron

Chapter 3.4: Non-Ferrous alloys

Non-Ferrous alloys – Overview



[CAM15]

Benefits of Alloying:

- Adaptation of aluminum properties to specific applications
- Enhances mechanical properties like strength, hardness, and wear resistance
- Improves casting characteristics and corrosion resistance

Main Alloy Groups: Based on the phases formed by the group's alloying elements

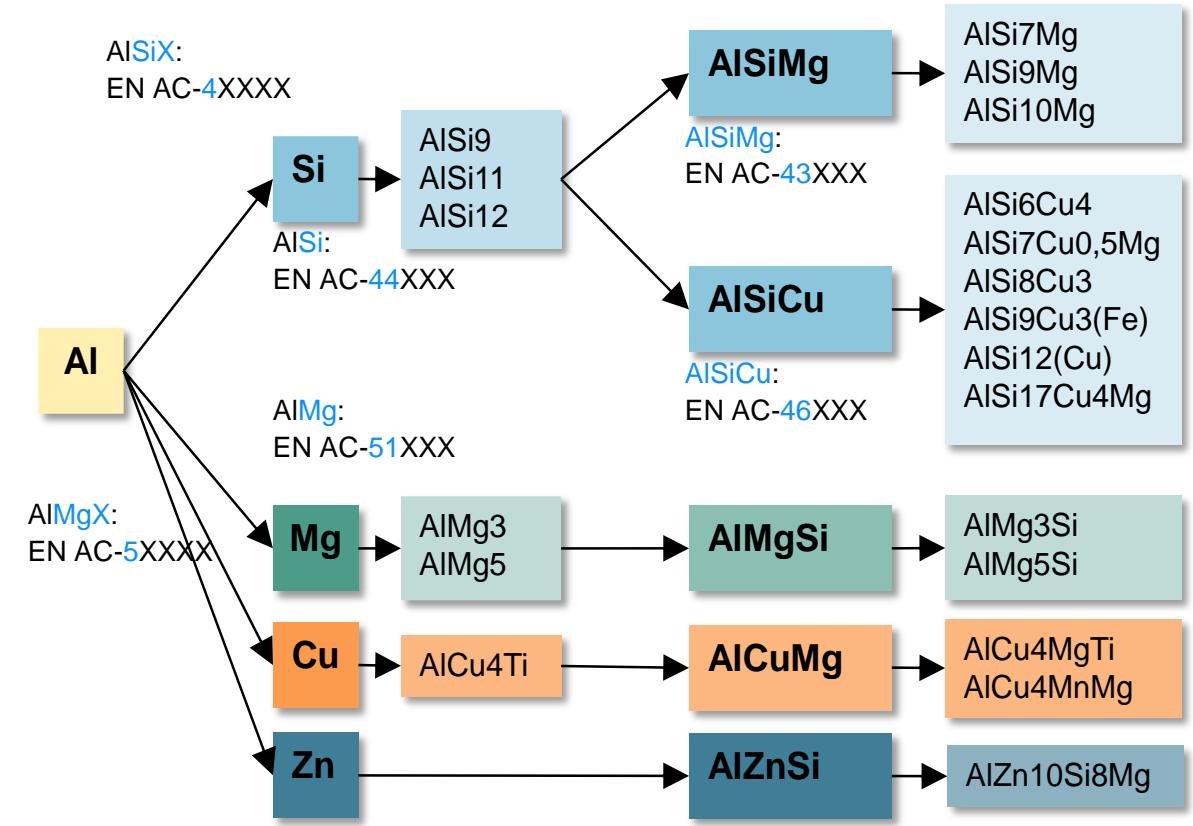
Example:

Group 4 (Si as the primary alloying element)

- Phases: α -Aluminum + Silicon (Eutectic)

Group 43 (Si and Mg as the primary alloying elements):

- Predominantly silicon-rich phases due to magnesium addition
- Phases: α -Aluminum + Silicon (Eutectic) + Mg_2Si (at the edges)



Non-Ferrous alloys – Aluminium alloy compositions

Silicon (Si)

- Purpose: Improves fluidity and reduces shrinkage in casting
- Application: Widely used in cast aluminum alloys (e.g., Al-Si family), enhances wear resistance

Magnesium (Mg)

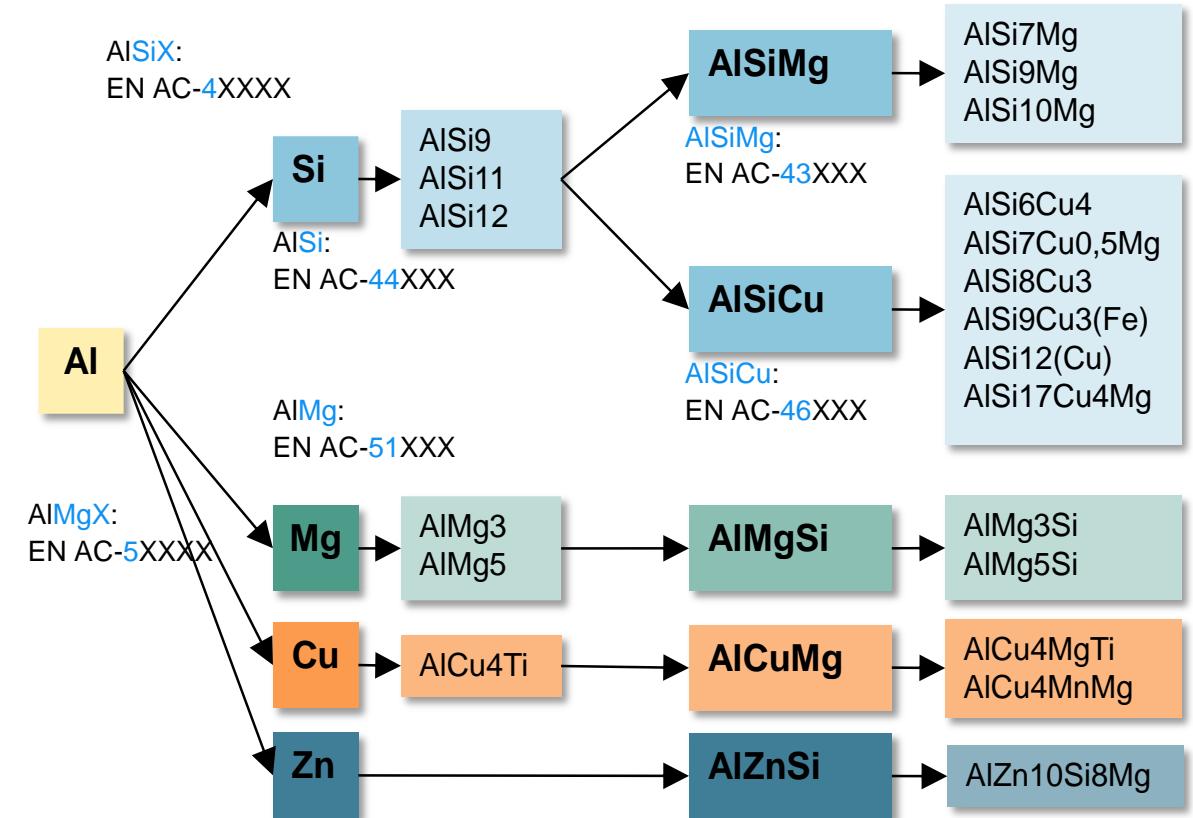
- Purpose: Increases strength and corrosion resistance
- Application: Forms Mg_2Si with silicon, strengthening the alloy, used in wrought alloys and high-pressure die castings

Copper (Cu)

- Purpose: Greatly increases mechanical strength, but at the expense of corrosion resistance
- Application: Common in aerospace alloys, important for heat-treatable alloys, improving hardness and durability

Zinc (Zn)

- Purpose: When combined with magnesium, it significantly increases strength
- Application: Key component in the 7xxx series (Al-Zn-Mg-Cu); used in high-strength aerospace components



Non-Ferrous alloys – Al alloys widely used in industry

Werkstoffbezeichnung				Werkstoff-zustand	mechanische Eigenschaften RT-Zugversuch				weitere Eigenschaften				
Legierungs-gruppe	chemische Symbole	numerisch	VDS-Nr. (alt)		Zugfestigkeit R _m [MPa]	Dehngrenze R _{p0,2} [MPa]	Bruchdehnung A [%]	Härte [HBW]	Warmfestigkeit bis 200 °C	Korrosions-beständigkeit	Wärme-leitfähigkeit [W/mK]	Duktilität	Ermüdungs-festigkeit [MPa]
Al	Al 99,6E	-	-	F	75	-	10	17	E	A	210	A	-
	Al 99,7E	-	-	F	75	-	10	17	E	A	210	A	-
AlSi10Mg	EN AC-Al Si10Mg(Fe)	EN AC-43400	239 D	F	240	140	1	70	C	C	130 ... 150	C	60 ... 90
	EN AC-Al Si10MnMg	EN AC-43500	-	F	250	120	5	65	C	B	140 ... 170	A	80 ... 90
				T5	270	150	4	80					
				T6	250	180	5	100					
				T7	200	120	12	60					
AlSi	EN AC-Al Si12(Fe)(a)	EN AC-44300	230 D	F	240	130	1	60	C	C	130 ... 160	C	60 ... 90
	EN AC-Al Si9	EN AC-44400	-	F	220	120	2	55	C	C	130 ... 150	C	60 ... 90
	EN AC-Al Si12(Fe)(b)	EN AC-44500	-	F	240	140	1	60	C	C		C	60 ... 90
AlSi9Cu	EN AC-Al Si9Cu3(Fe)	EN AC-46000	226 D	F	240	140	<1	80	B	D	110 ... 120	D	60 ... 90
	EN AC-Al Si11Cu2(Fe)	EN AC-46100	-	F	240	140	<1	80					
	EN AC-Al Si8Cu3	EN AC-46200	-	F	240	140	1	80	A	D	110 ... 130	C	60 ... 90
	EN AC-Al Si9Cu3(Fe)(Zn)	EN AC-46500	226/3	F	240	140	<1	80	A	D	110 ... 120	D	60 ... 90
AlSi(Cu)	EN AC-Al Si12Cu1(Fe)	EN AC-47100	231 D	F	240	140	1	70	B	E	120 ... 150	C	60 ... 90
AlSiCuNiMg	EN AC-Al Si17Cu4Mg	EN AC-48100	-	F	220	160	<1	90	B	D	120 ... 130	E	60 ... 90
AlMg	EN AC-Al Mg9	EN AC-51200	349	F	200	130	1	70	B	A	60 ... 90	C	60 ... 90
	EN AC-Al Mg5Si2Mn*	EN AC-51500	-	F	250	140	5	70	B	A	110 ... 130	A	80 ... 110
AlSi9Mn	AlSi9Mn	-	-	F	200	110	8	70	A	A	110 ... 130	-	-

[VDD16]

Structural casting alloys

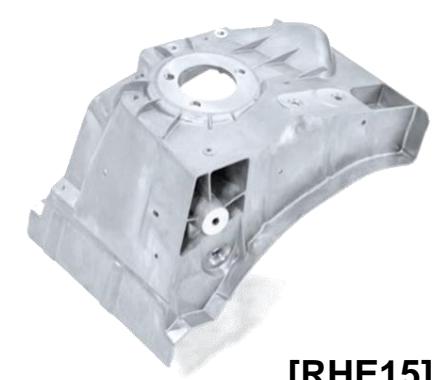
General-purpose alloy for housing components; high proportion of secondary aluminum possible

Corrosion-resistant alloys

Non-Ferrous alloys – Some examples showing the use of different Al alloys

AlSiMnMg

- For high ductility requirements, usually after heat treatment
- Good corrosion resistance, but limited high-temperature strength
- Usually preferred in vehicle (structural) construction



AlSi12 variants

- Thin-walled, very good casting properties
- Vibration and impact-resistant components
- Complex component geometries; usually pumps



Non-Ferrous alloys – Some examples showing the use of different Al alloys

AISiCu variants

- For increased heat resistance requirements thicker-walled components: engine blocks, cylinder heads, gearbox housings
- Poor corrosion properties
- Alloy composition very tolerant
→ high proportion of secondary alloys
→ economically/ ecologically advantageous



Intake manifold and turbocharger
Material: EN AC-AISi8Cu3
[ACT21]

AlMg AlMgSi AlSiMn

- For high corrosion requirements and ageing-resistant structural bonding
- In vehicle construction: often with a requirement profile of high ductility/strength in a corrosive environment



Chassis component
Material: EN AC-AlMg5Si2Mn
[RHE15]



Anchor for ocean-going sailors
Material: Anticorodal 72 / AISi7Mg0.6
[RHE21b]

Gearbox housing outboard motor
Material: Modified AISi10MnMg

Source: ZF Marine



Chapter 3.5: Heat treatment of Al-alloys

Heat treatment of Al-alloys

Key Benefits

- Enhanced mechanical properties: improved strength, hardness, and ductility
- Tailored to specific application needs by modifying process parameters

Solution Heat Treatment

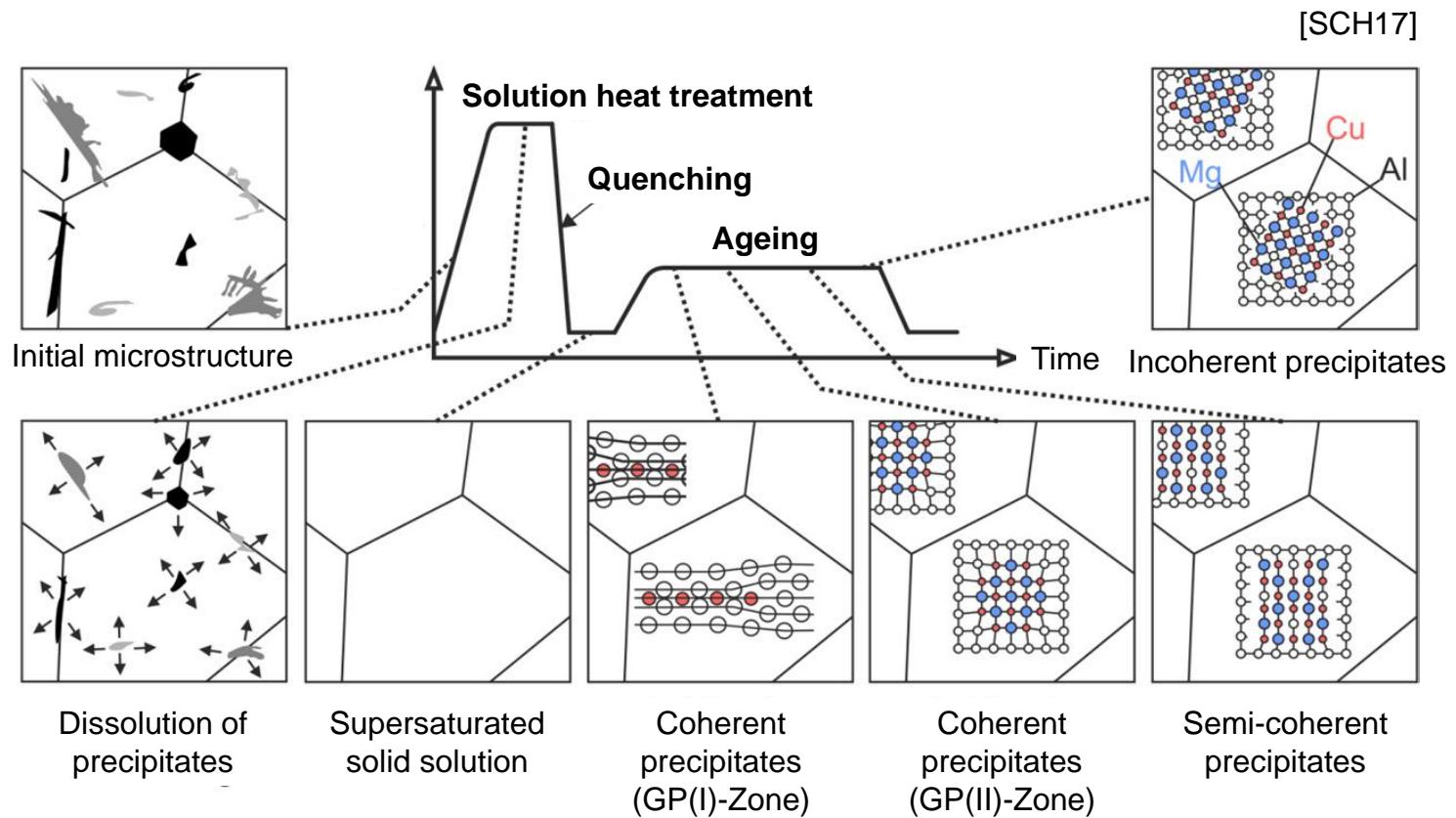
- Heat alloy to high temperature to dissolve elements
- Specific temperature and duration vary by alloy

Quenching

- Rapid cooling, typically via water quenching
- Creates a supersaturated, non-equilibrium state

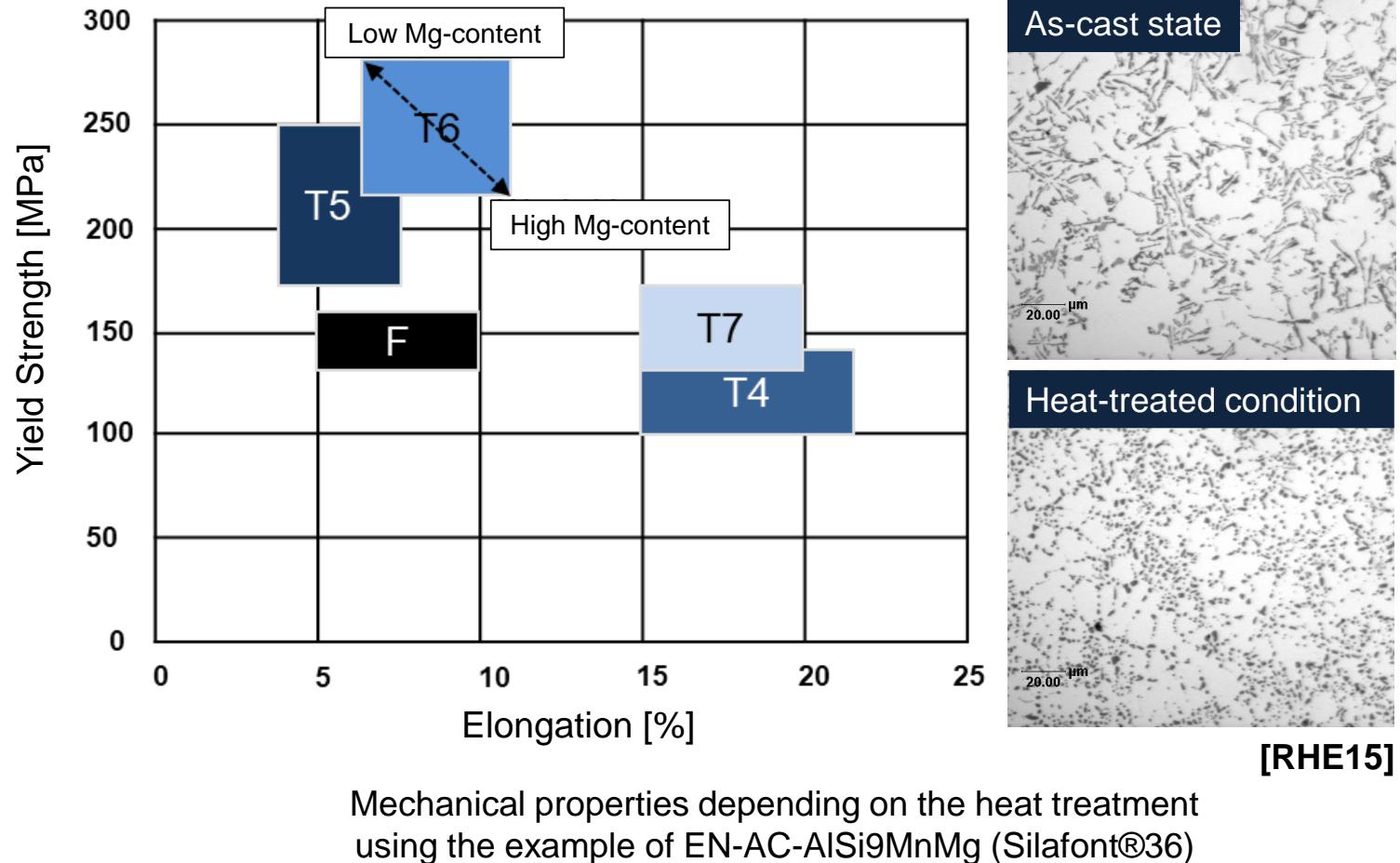
Aging

- Natural (at room temperature) or Artificial (at elevated temperatures)
- Artificial aging: Heat below solution treatment temperature for a set period
- Leads to precipitation of elements, increasing strength.



Heat treatment of Al-alloys

- Heat treatment conditions for aluminum alloys; each of these heat treatments is designed to achieve specific mechanical properties:
 - 0** = Annealed
 - T1** = Quenched and naturally aged
 - T4** = Solution heat-treated and naturally aged
 - T5** = Quenched and artificially aged
 - T6** = Solution heat-treated and artificially aged
 - T7** = Solution heat-treated and overaged/overhardened
- The ranges of the different heat treatments result from the bandwidths of the chemical composition and the heat treatment
- The scatter within the alloy composition leads to deviating mechanical properties even with identical heat treatment parameters



Chapter 4: Designing a successful casting process

Designing a successful casting process

Ten general aspects for a successful casting process

1. Understanding Material Properties:

- Choose suitable casting materials based on mechanical properties, melting temperature, and solidification behavior

2. Design for Manufacturability:

- Simplify geometry to minimize undercuts and complex features
- Ensure uniform wall thickness to prevent hotspots and reduce shrinkage defects

3. Incorporating Draft Angles:

- Include draft angles in vertical surfaces to facilitate easy removal from molds

4. Mold Considerations:

- Design molds to compensate for metal shrinkage and cooling contractions.
- Use risers and gating systems to ensure proper metal flow and solidification

5. Allowance for Machining and Finishing:

- Provide additional material for post-casting machining processes
- Anticipate surface finish requirements and dimensional tolerances

Designing a successful casting process

Ten general aspects for a successful casting process

6. Avoiding Stress Concentrations:

- Radius internal corners and fillets to reduce stress concentration
- Avoid sudden changes in cross-sectional areas

7. Design for Soundness:

- Position internal cavities to minimize trapped gases and shrinkage porosity
- Use cores effectively to create hollow sections and reduce weight

8. Thermal Management in Design:

- Analyze heat flow to manage cooling rates and solidification patterns
- Design for directional solidification from the thinnest to the thickest section

9. Feeding and Risers:

- Design feeding paths to deliver molten metal to all regions during solidification
- Size and place risers to compensate for shrinkage without causing discontinuities

10. Quality Assurance:

- Implement a robust inspection plan for critical dimensions and defects
- Use simulation tools to predict and address potential casting issues during design

Designing a successful casting process

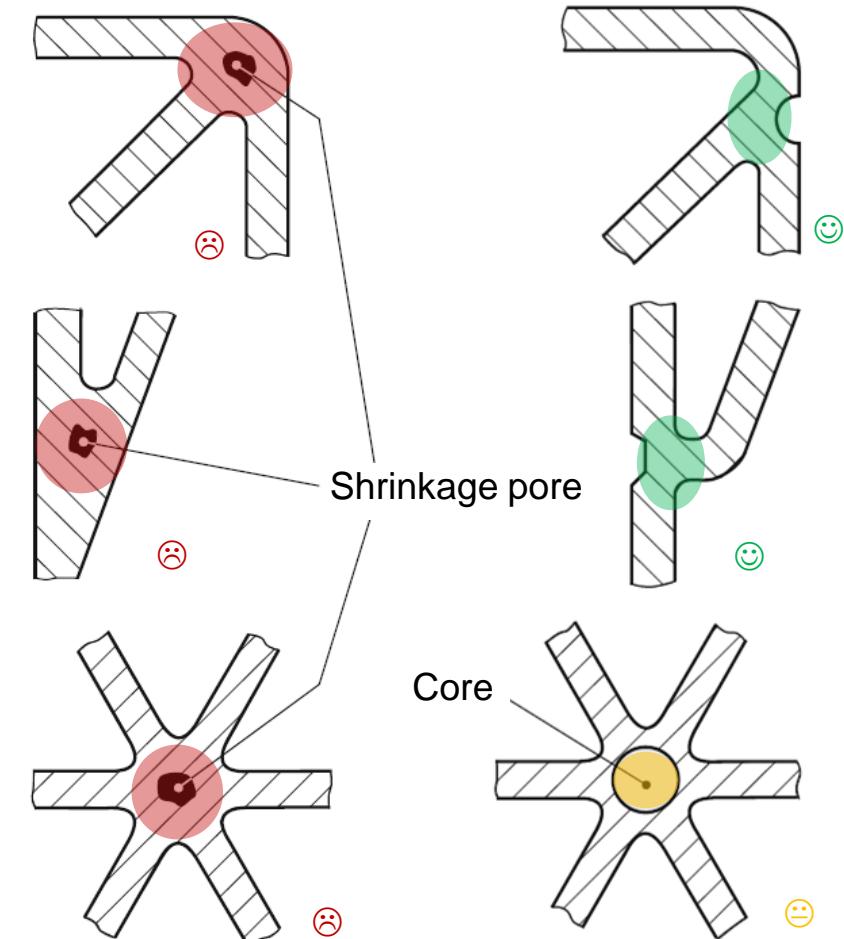
Design for Manufacturability

2. Reducing material concentrations in casting designs is vital for several reasons:

- Even Cooling and Solidification: Thick sections cool slower, leading to uneven solidification. This can cause internal stresses, distortion, and cracking
- Minimize Shrinkage Defects: Thick areas are prone to shrinkage cavities as they remain molten longer and may not be adequately fed by the risers
- Material Efficiency: Reducing material concentrations leads to more efficient use of material, reducing weight and cost

Design Strategies:

- Strive for uniformity in wall thickness to ensure consistent cooling rates
- Coring Out Large Sections: Replace large solid areas with hollow sections or use cores to maintain strength while reducing mass

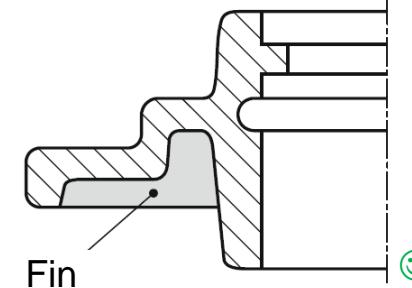
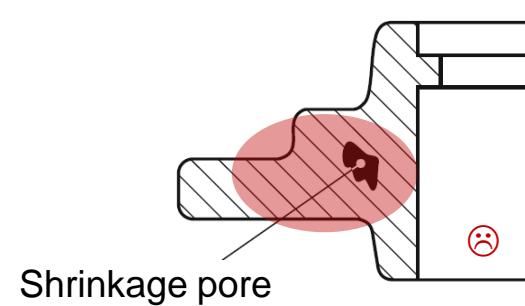
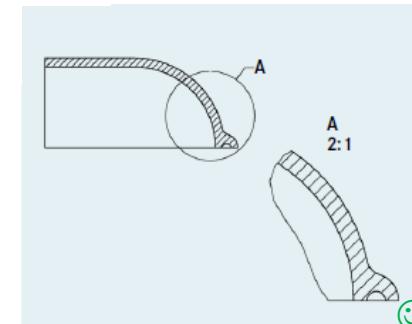
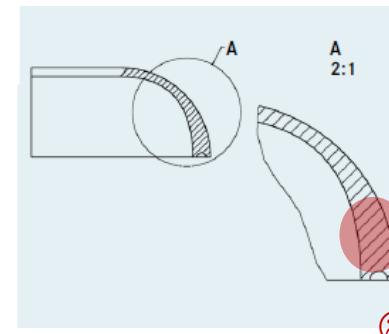
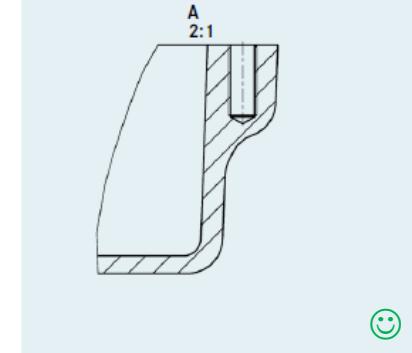
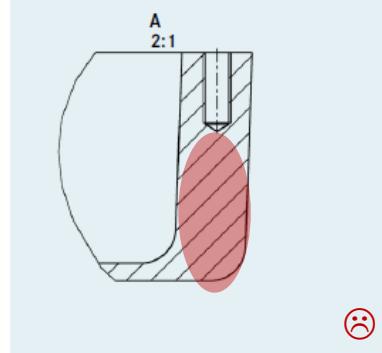
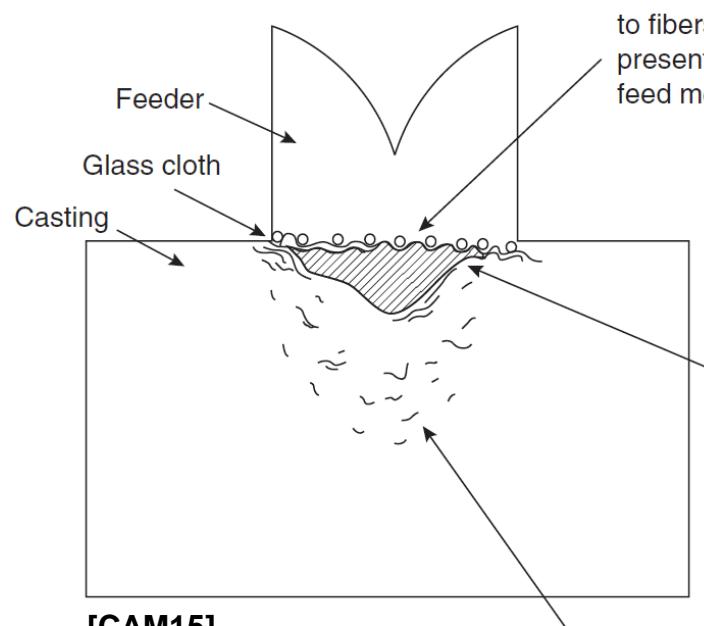


Designing a successful casting process

Design for Manufacturability

2. 4. 9.

Design for Manufacturability Mold Considerations Feeding and Risers



Designing a successful casting process

Incorporating Draft Angles

3. **Definition:** A taper given to vertical faces of a mold to facilitate part removal

Purpose:

- Ensures smooth ejection of the cast part
- Reduces mold wear and tear

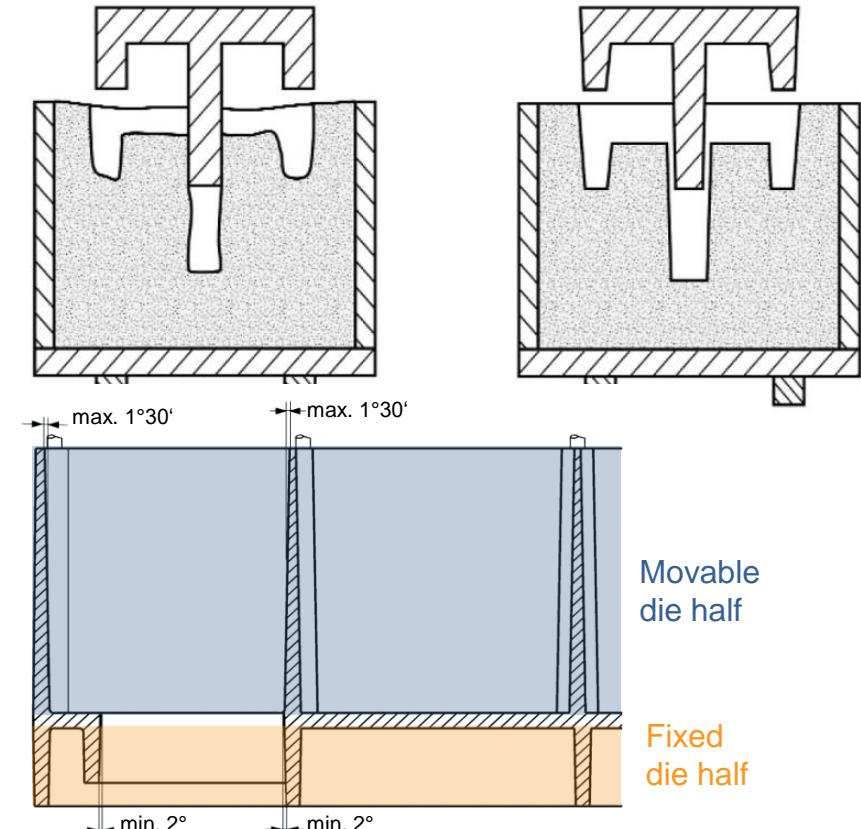
Angle Selection:

- Varies with part size, complexity, and material
- Typical ranges: 1° to 3° for metals (may vary)

Design Consideration:

- Balance between functionality and aesthetics
- Should align with uniform wall thickness for even cooling

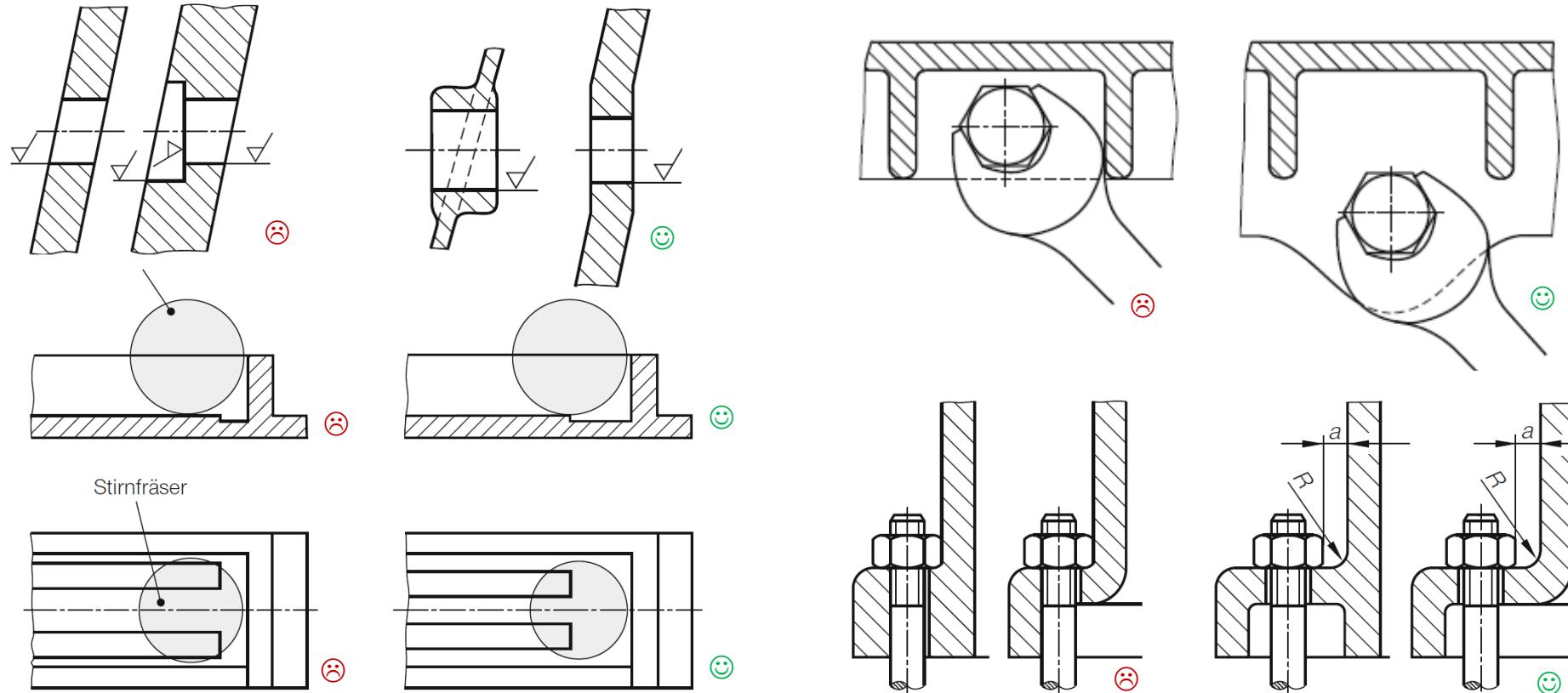
Application: Essential in sand casting, die casting, investment casting; crucial for efficiency in automated, high-volume casting processes



Designing a successful casting process

Allowance for machining and finishing

5. Example of post-processing-compatible designs: Increased accessibility for downstream cutting and joining operations, e.g. screw connections



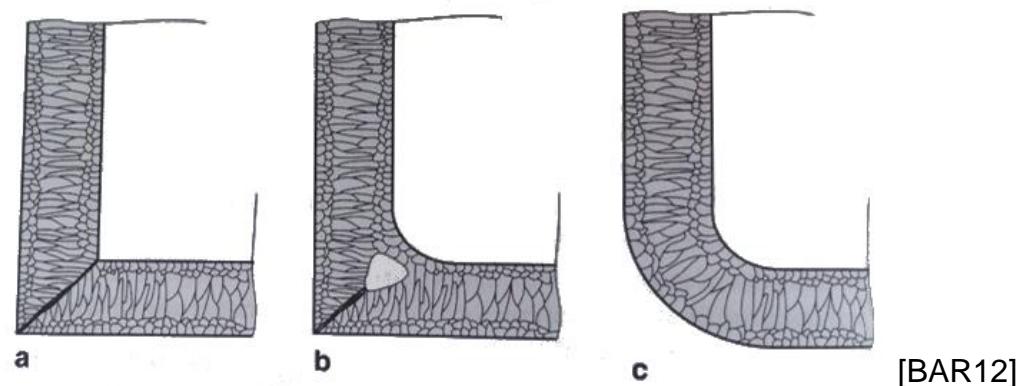
Designing a successful casting process

Avoiding Stress Concentrations

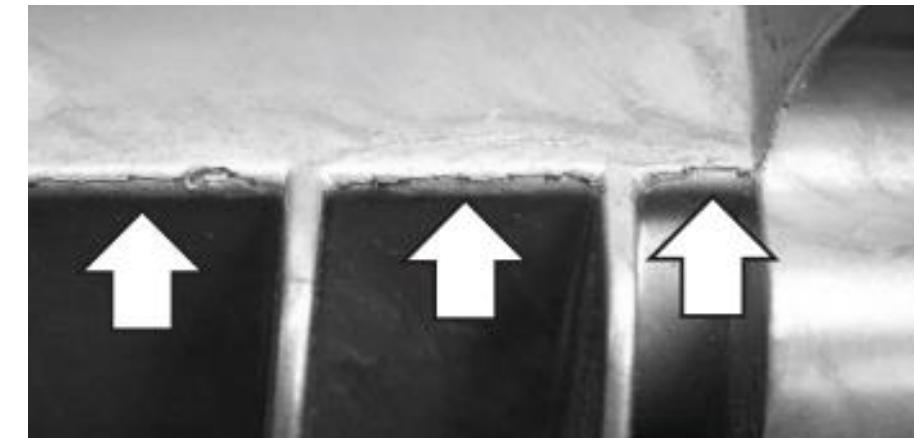
6. Sharp edges in casting design are prone to defects and weaknesses due to the following reasons:
- **Stress Concentration** (mold and casting): Sharp edges create points of high stress concentration, leading to cracks and failure under load
 - **Flow Disruption**: During casting, molten metal flow can be turbulent around sharp edges, leading to incomplete filling or cold shuts
 - **Cooling Irregularities**: Sharp corners cool faster than the rest of the material, causing differential shrinkage and residual stress

Critical in all types of casting processes, particularly where mechanical strength and reliability are paramount

Design Solutions: Incorporate Fillets and Radii – use smooth curves instead of sharp transitions; fillets (rounded internal corners) and radii (rounded external corners) reduce stress concentration



[BAR12]



[NAD21]

Schematic sketch of negative examples (a,b) and avoidance (c)

Designing a successful casting process

Thermal Management in Design

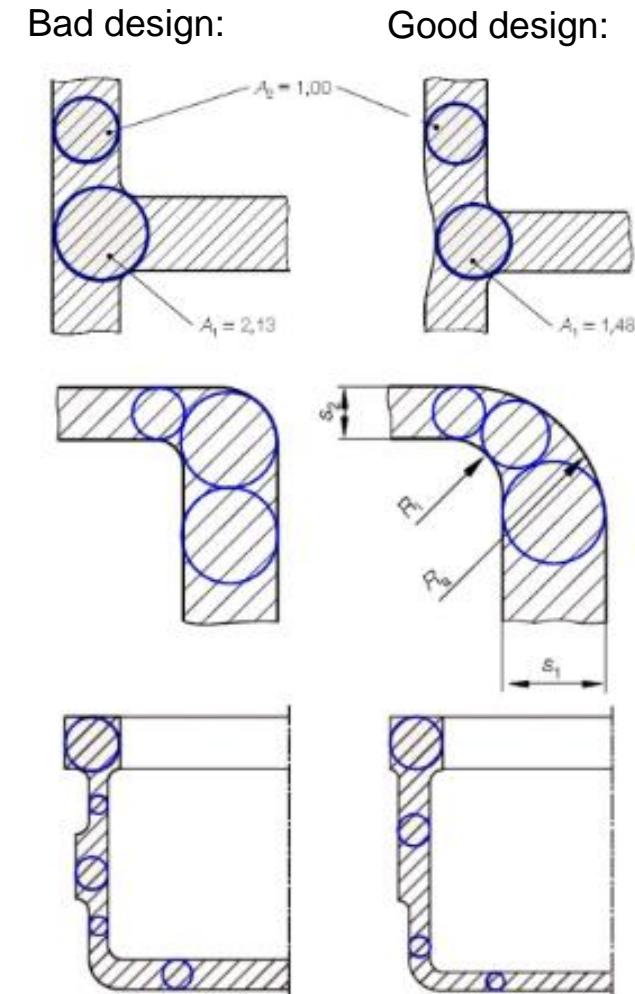
8. **Concept:** Controlled solidification of molten metal from one end of the mold to the other

Purpose:

- Minimizes defects like shrinkage cavities and porosity
- Ensures a uniform and fine grain structure

Process and design strategy:

- Begins at the coolest part of the mold (usually near the mold walls); progresses towards the risers, which stay molten longer to feed the solidifying metal
- Mold and casting design should facilitate a steady, unidirectional flow of heat
- Risers and chills are strategically placed to control cooling rates and solidification path



End of the lecture unit *Casting Technology*

Thank you for your listening!