LTU Casting Course 2025 & METACAST webinar

Solidification Fundamentals

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Luleå, 28 Nov 2025

SWERIM Casting Course & LTU lectures on Casting - Process metallurgy Department

SWERIM

LULEÅ TEKNISKA UNIVERSITET

	Topic	
18-Nov	**Session 1 - LTU**	**Room No**
10:15-12:00	Intro to industrial casting	LTU, E247
12:00-13:00	Lunch	
13:00-14:00	Solidification 1	
14:00-15:00	Phase diagrams	
15:00-16:15	Thermocalc intro & examples	

25-Nov	**Session 2 - SWERIM**	Room
10:00-12:00	Casting experiment SWERIM	Swerim, Melderstein (am) & Svanstein (pm)
12:00-13:00	Lunch	
13:00-14:30	Casting modelling I	
14:30-15:00	Break	
15:00-16:30	CFD for continuous casting	

28-Nov	**Session 3 - SWERIM + SSAB**	Room
10:15-12:00	Solidification II + METACAST webinar	Swerim, Svanstein
12:00-13:00	Lunch	
13:00-16:00	SSAB visit	

02-Dec	**Session 4 - LTU**	Room
10:15-12:00	Casting modelling II	LTU, E247
12:00-13:00	Lunch	
13:00-14:30	Defects and their origin	
14:30-15:30	Characterization techniques	

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Solidification II - WEBINAR

Fundamentals and modelling
Industrial measurements and validation

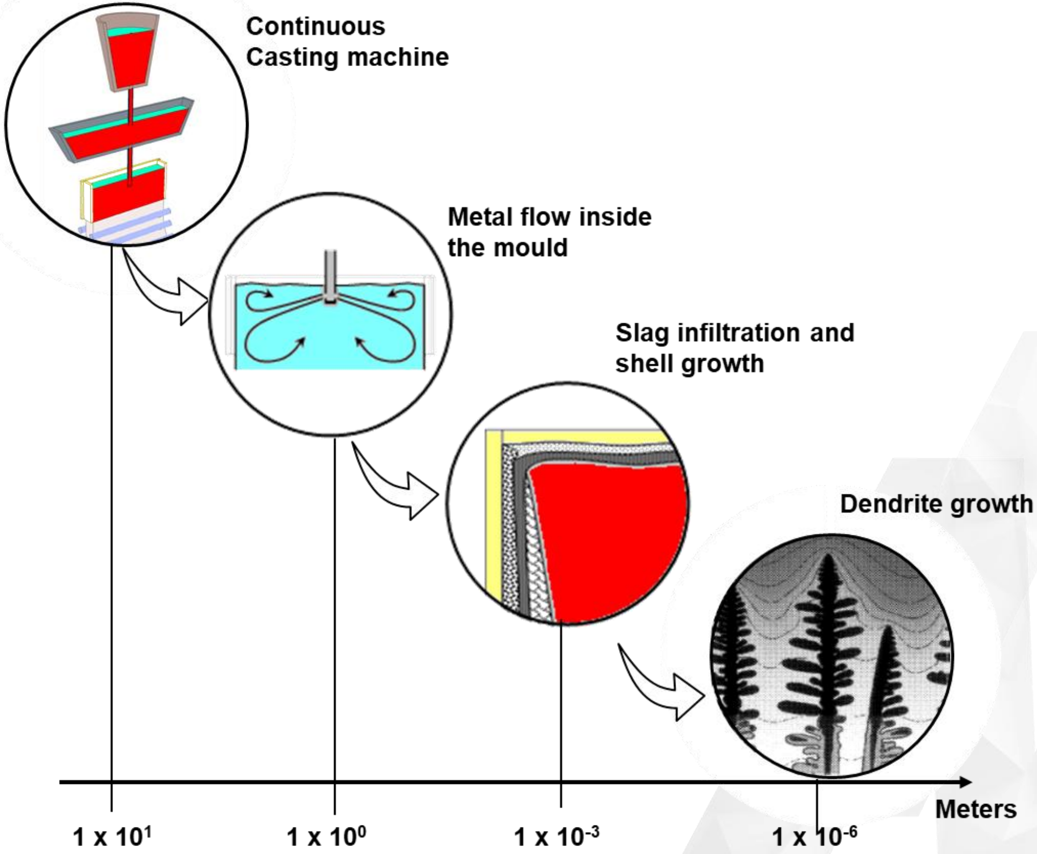
Join us for an in-depth session on solidification fundamentals!

*We will explore key concepts including nucleation, heat and mass transfer, fluid flow principles, microstructure modelling, stress–strain analysis, and advanced characterization and validation techniques. As part of the discussion, two EU-funded RFCS projects—**Shell-Crack** and **SUNSHINE**—will be showcased as case studies, highlighting practical applications and research insights.*

Time	Topic
10:00-10:15	Welcome
10:15-11:30	Solidification Fundamentals
11:30-11:45	Q&A session
11:45-13:00	Lunch break
13:00-13:45	Introduction to solidification modelling
13:45-14:15	RFCS Shell-Crack
14:15-14:45	RFCS SUNSHINE
14:45-15:15	Industrial measurement techniques for model validation
15:15-15:30	Final Q&A session and End of seminar

Solidification Basics

Casting length scales



Solidification scales

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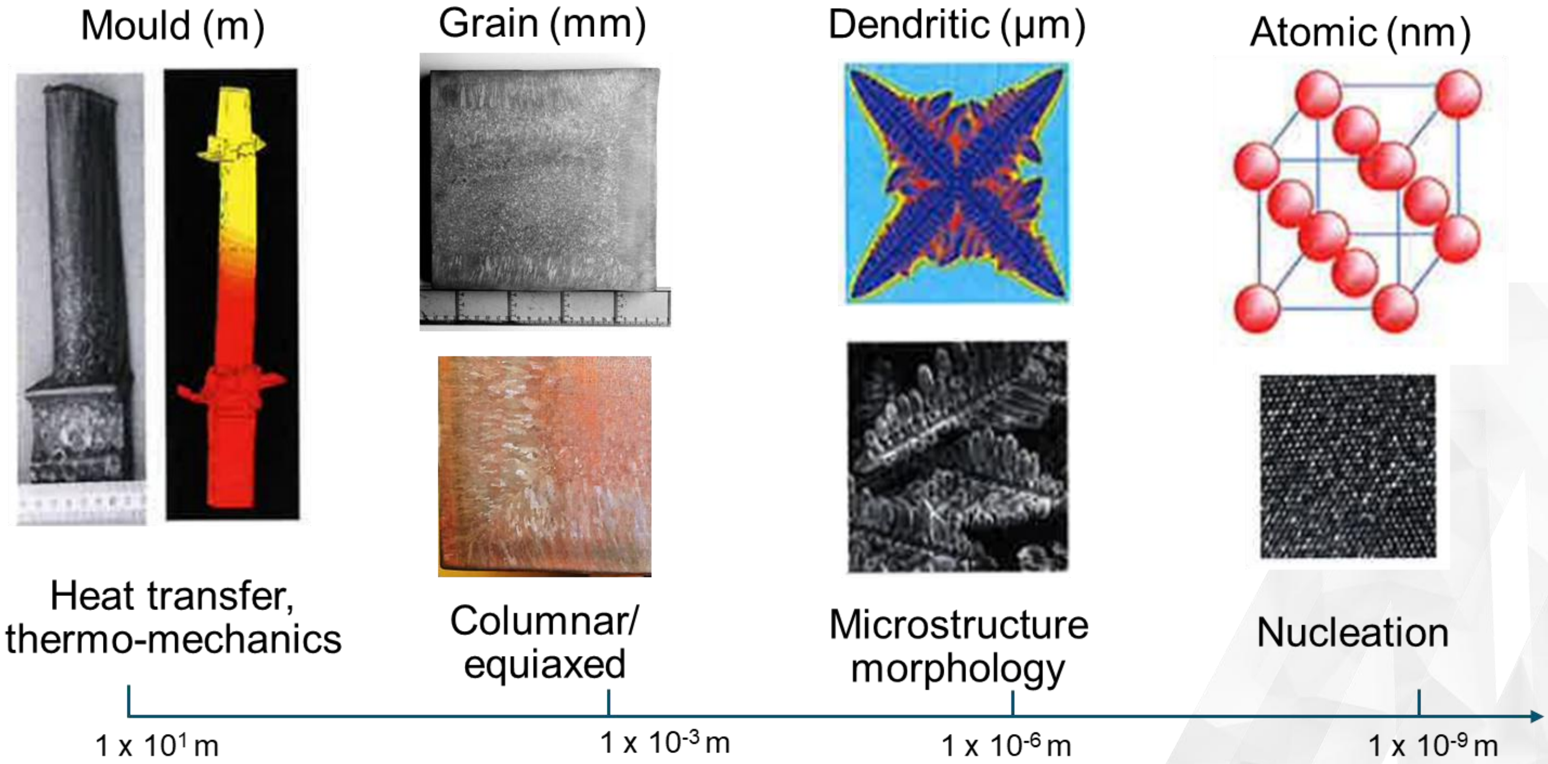

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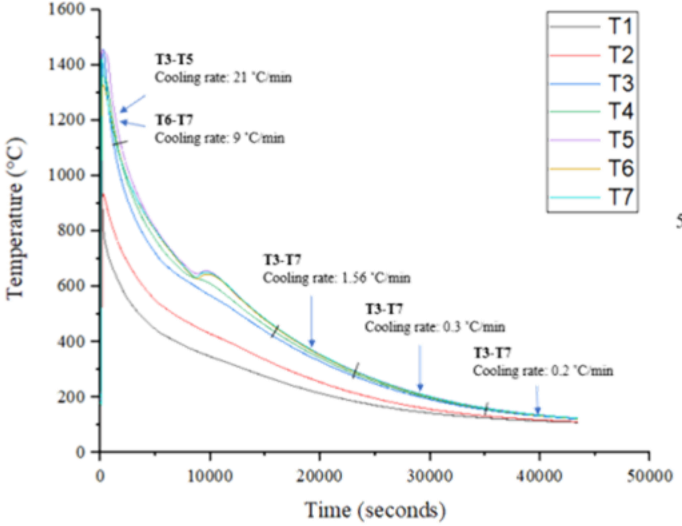
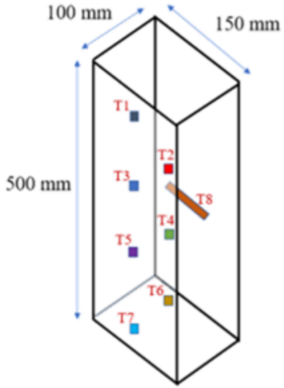
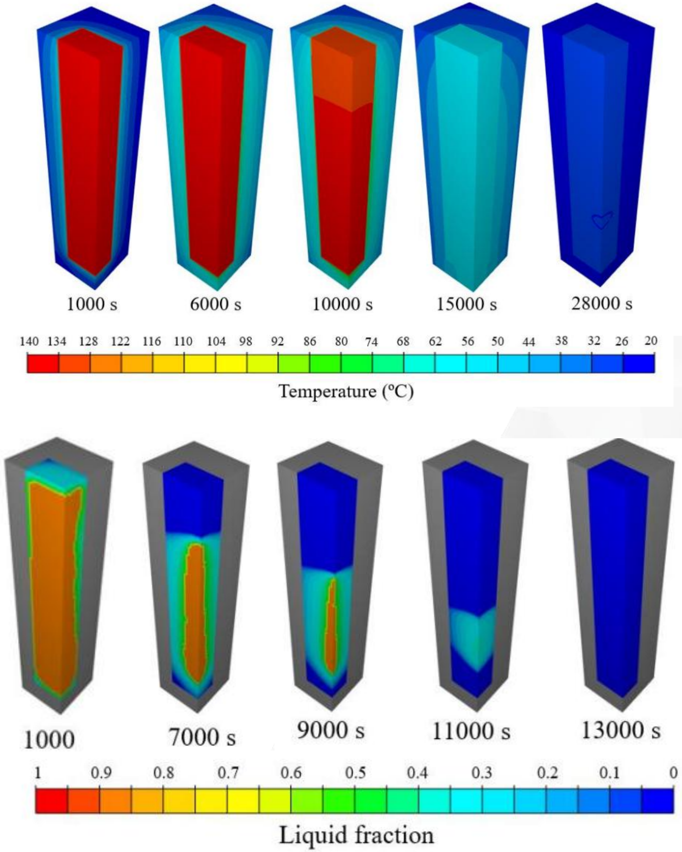
At macro level: Cooling rate in casting

Overall cooling rate and local cooling rate concepts

$$Cs = \frac{\Delta T}{time}$$

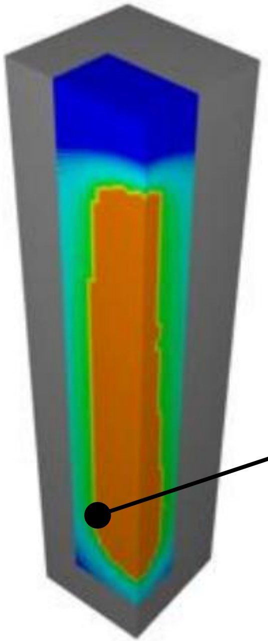


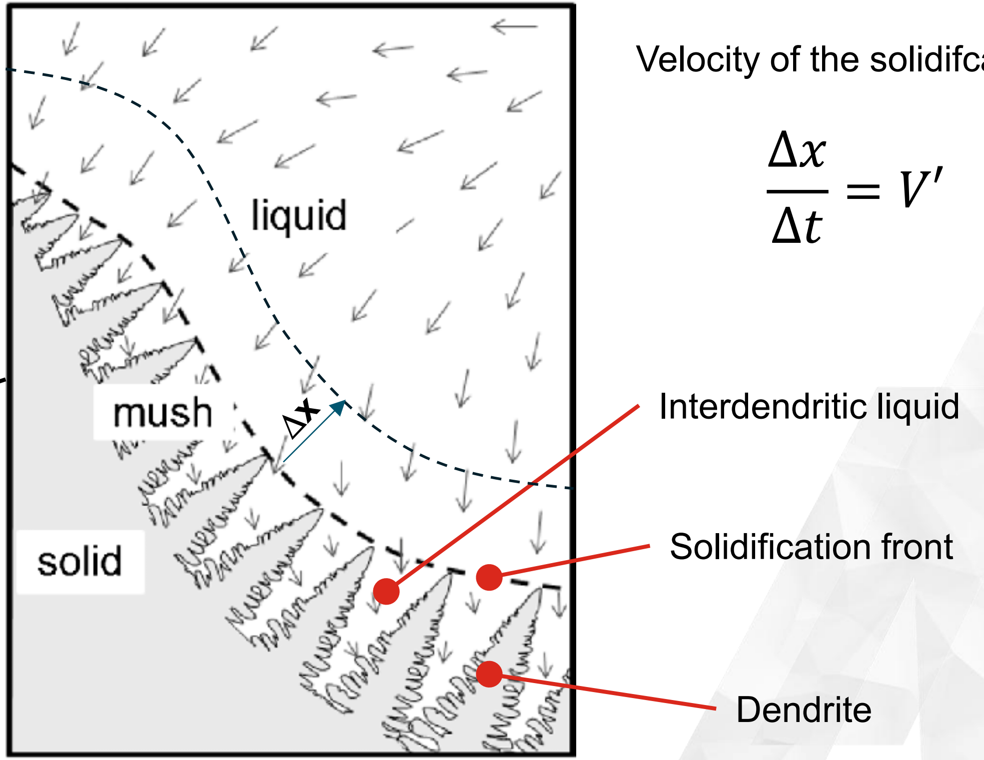




Hedman, D. (2020). Casting and Characterization of Advanced High Strength Steels (MSc Dissertation). LTU

At micro level: microstructure growth





Velocity of the solidifcation front:

$$\frac{\Delta x}{\Delta t} = V'$$

Vakhrushev, Alexander & Wu, Menghuai & Ludwig, Andreas & Tang, Yong & Hackl, Gernot & Nitzl, Gerald. (2014). Numerical Investigation of Shell Formation in Thin Slab Casting of Funnel-Type Mold. Metallurgical and Materials Transactions B. 45. 10.1007/s11663-014-0030-2.

Resulting macrostructure

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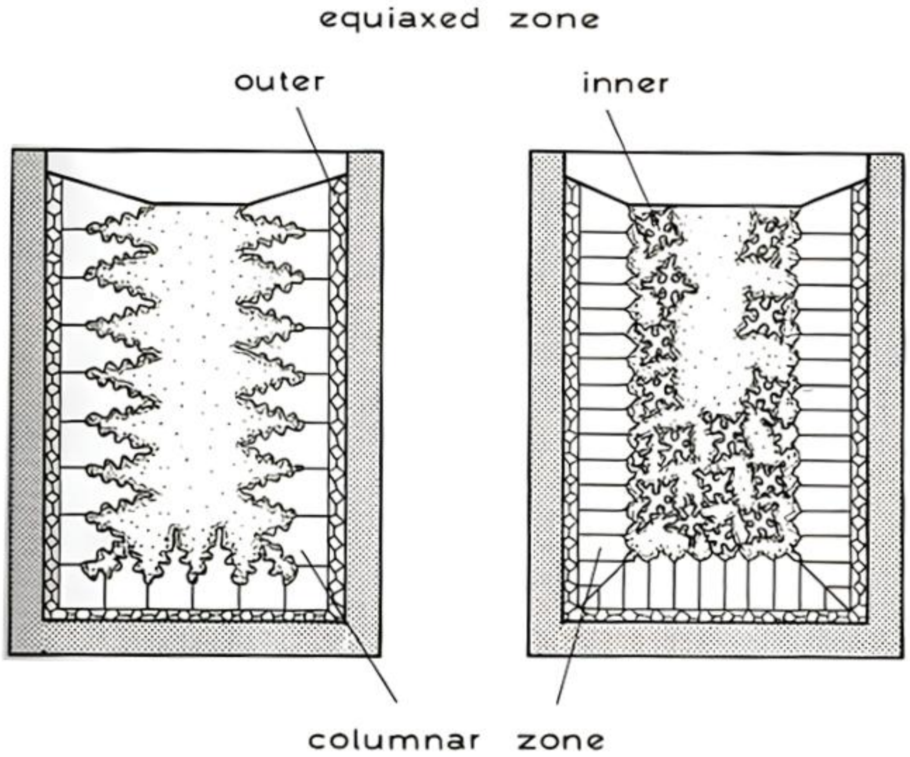
https://www.phase-trans.msm.cam.ac.uk/2010/ingots.html



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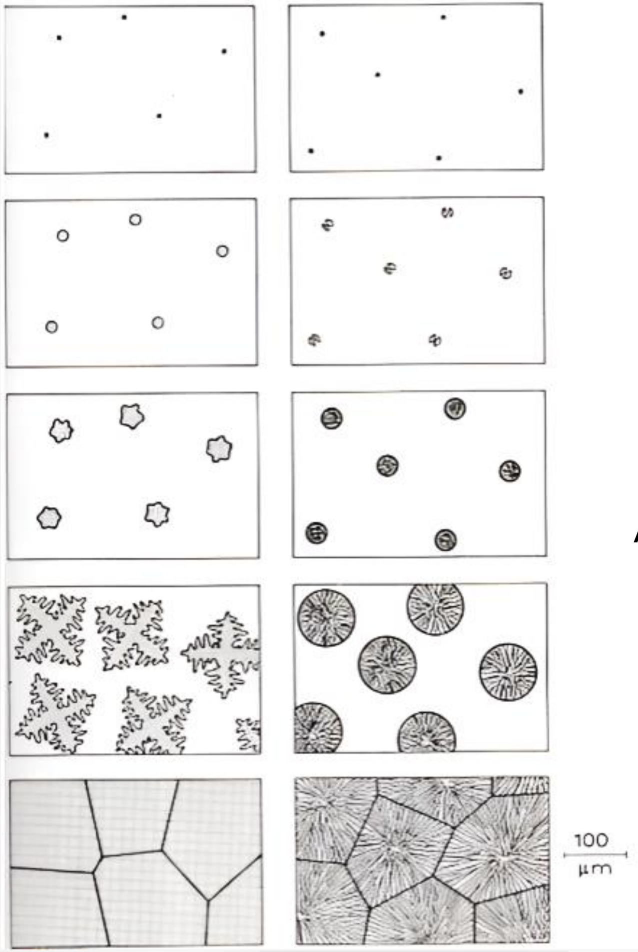
Kurz, W., & Fisher, D. J. (1998). Solidification Microstructure: Cells and Dendrites. In *Fundamentals of Solidification* (pp. 80-87). Enfield, NH: Trans Tech Publications.

Nucleation

Pure metal



Alloy

Kurz, W., & Fisher, D. J. (1998). Solidification Microstructure: Cells and Dendrites. In *Fundamentals of Solidification* (pp. 80-87). Enfield, NH: Trans Tech Publications.

Free energy change, *ΔG*

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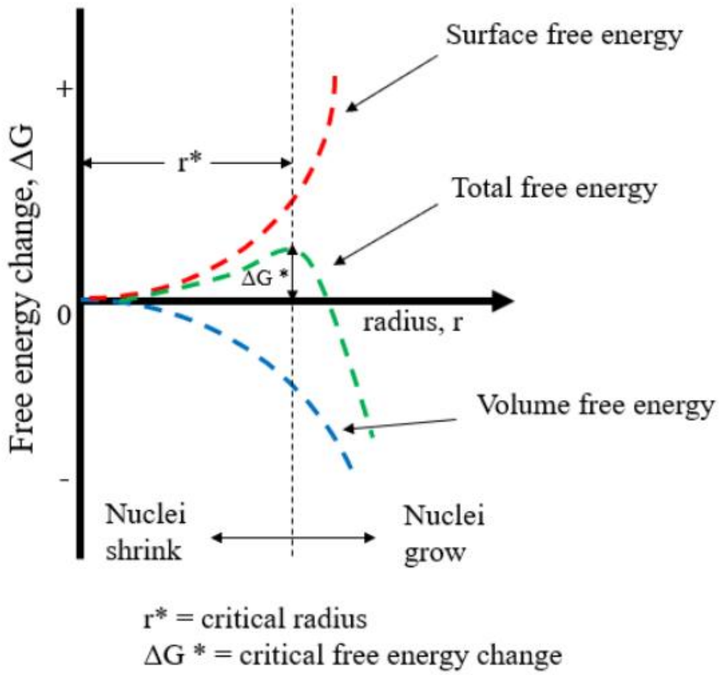
- Atoms in a melt vibrate and collide randomly which is the source of energy in the system.
- The thermal energy of the system decreases during cooling to a point at which **nuclei** are formed, which may occur hundreds of degrees C° below the freezing point since nucleation requires a certain amount of energy for the nuclei to reach a **critical radius**.
- If the nucleus does not reach this critical size, it will eventually dissolve before any growth starts; so, it is possible to decrease the temperature of a melt below the solidus temperature without solidifying. This is referred to as **undercooling**.
- In contrast, in a solid metal, the atoms are packed closely and well-defined in a crystallographic structure that requires the least amount of energy to remain stable.
- This ultimately defines the steel phase (e.g. body-centred cubic, BCC or face-centred cubic, FCC). [10] [11].



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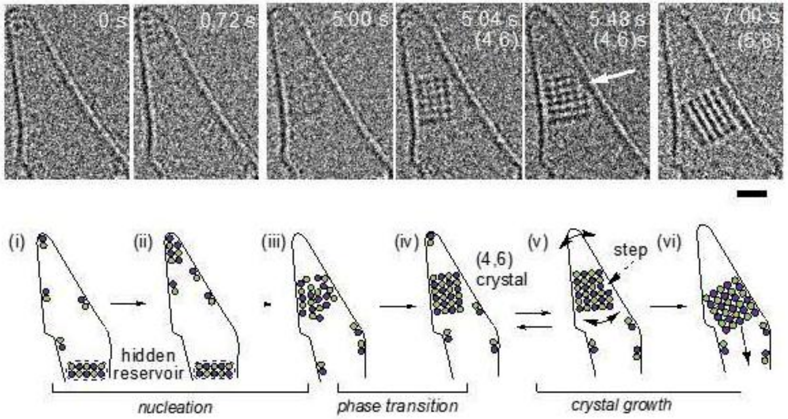
Hedman, D. (2020). Casting and Characterization of Advanced High Strength Steels (MSc Dissertation). LTU

First-ever atomic resolution video of salt crystals forming in real time

by University of Tokyo



A sodium chloride crystal growing in a vibrating carbon nanohorn. Credit: © 2021 American Chemical S…

Two novel techniques, atomic-resolution real-time video and conical carbon nanotube confinement, allow researchers to view never-before-seen details about crystal formation. The observations confirm theoretical predictions about how salt crystals form and could inform general theories about the way in which crystal formation produces different ordered structures from an otherwise disordered chemical mixture.

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Takayuki Nakamuro, Masaya Sakakibara, Hiroki Nada, Koji Harano, Eiichi Nakamura. Capturing the Moment of Emergence of Crystal Nucleus from Disorder. *Journal of the American Chemical Society*. DOI: 10.1021/jacs.0c12100

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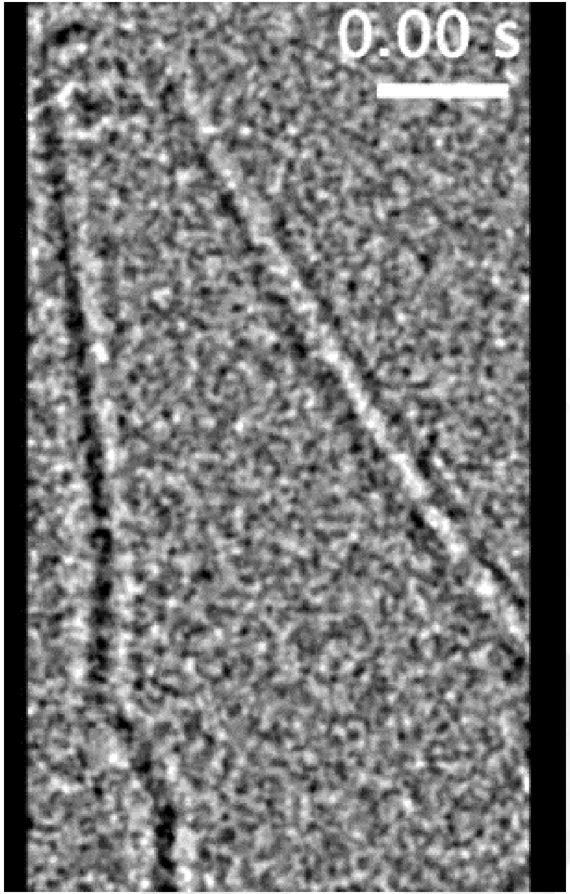
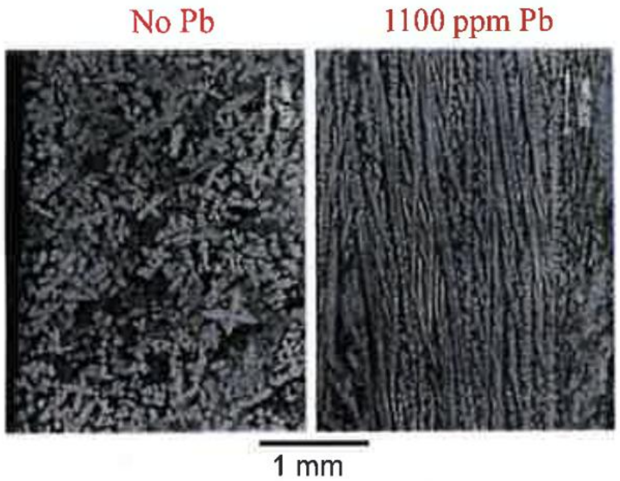


Sodium chloride growth in action. Credit: © 2021 American Chemical Society

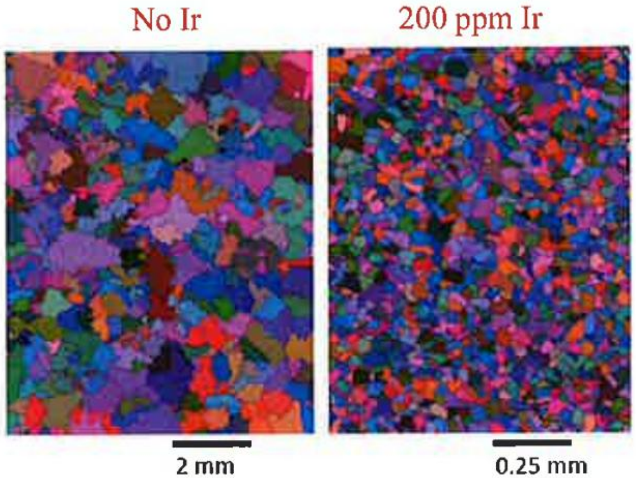
Nucleation affected by solute elements

Grain size and microstructure (nucleation) are not only influenced by the addition of particles, but also by some specific solute element additions.



"Contamination" of nucleation centers by Pb during solidification (DS) of Zn-3%Al

[A. Sémoroz, PhD thesis #2427, EPFL (2001)]



Reduction of grain size in yellow gold by the addition of Ir

[G. Kurtuldu et al, Acta mater. 70:240 (2014)]

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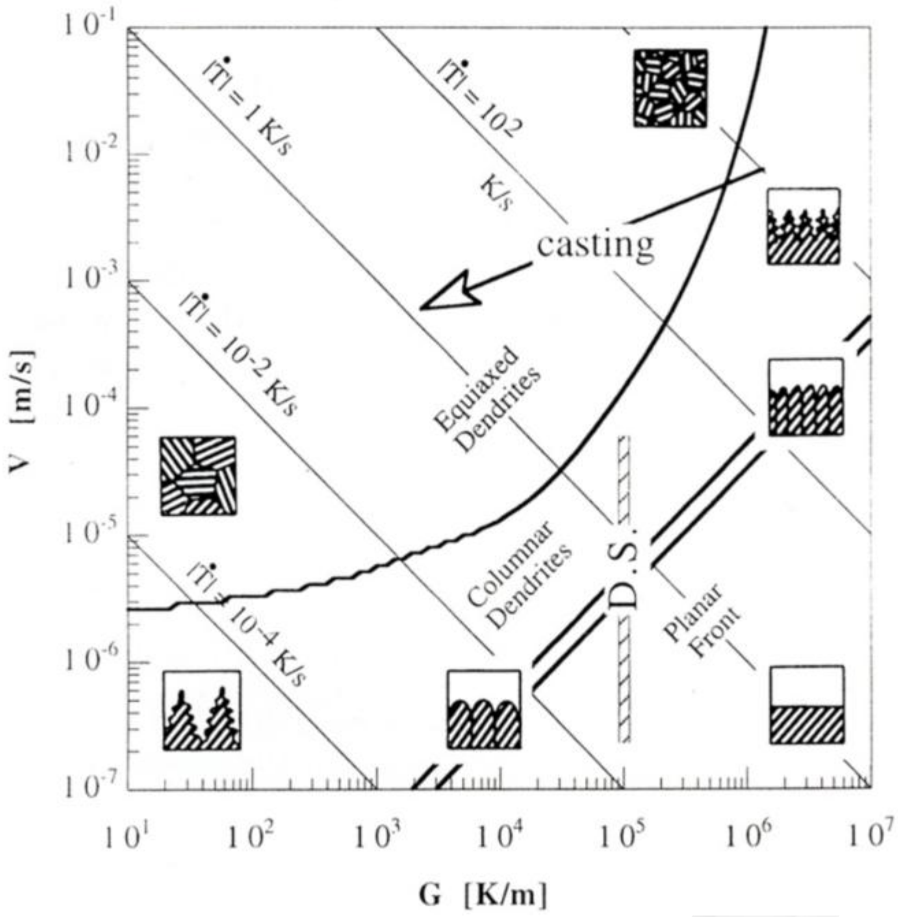
Solidification modes



Kurz, W., & Fisher, D. J. (1998). Solidification Microstructure: Cells and Dendrites. In *Fundamentals of Solidification* (pp. 80-87). Enfield, NH: Trans Tech Publications.

Solid/liquid interface morphology and Temperature

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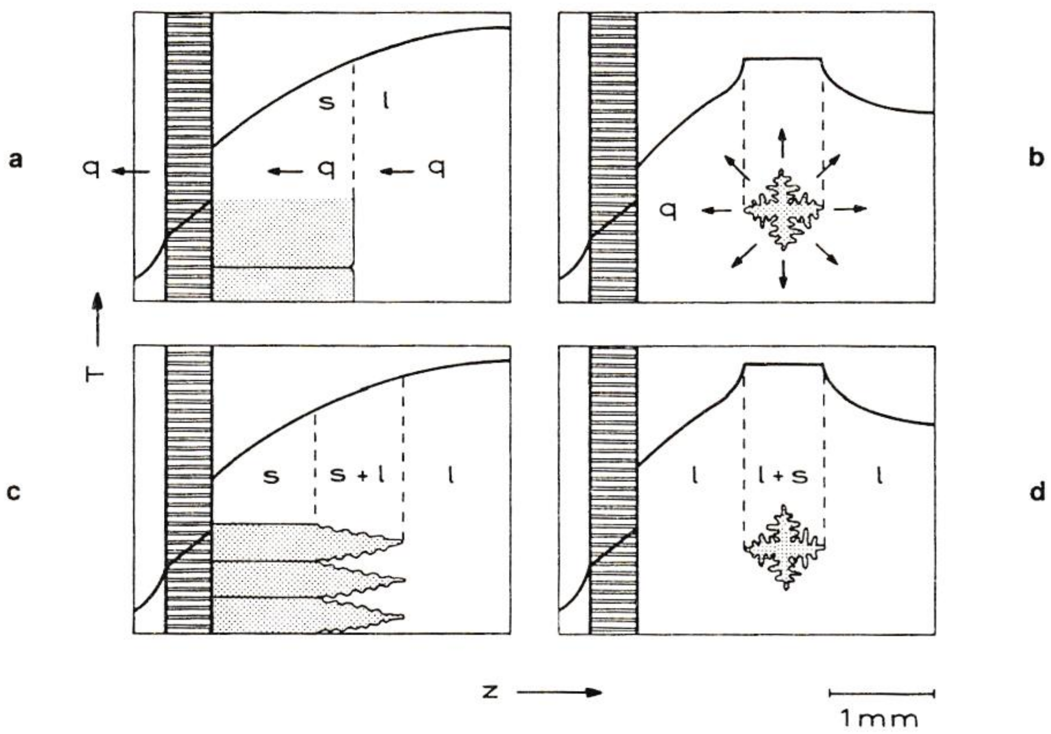

In a pure metal:

- At the mould wall, columnar grains generate a planar interface advancing opposite to heat flow (a)
- In the melt, dendrites grow radially in same direction as heat flow (b)

In Alloys:

- Morphology at mould wall is usually dendritic (Columnar) (c)
- Equaixed growth is similar to pure metals (d)

Note: In columnar growth, the hottest part is the melt, while in equiaxed, the crystals are hottest, So, the melt must be always cooled below melting point (i.e. undercooled) before equiaxed crystals can grow

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Kurz, W., & Fisher, D. J. (1998). Solidification Microstructure: Cells and Dendrites. In *Fundamentals of Solidification* (pp. 80-87). Enfield, NH: Trans Tech Publications.

Solidification examples

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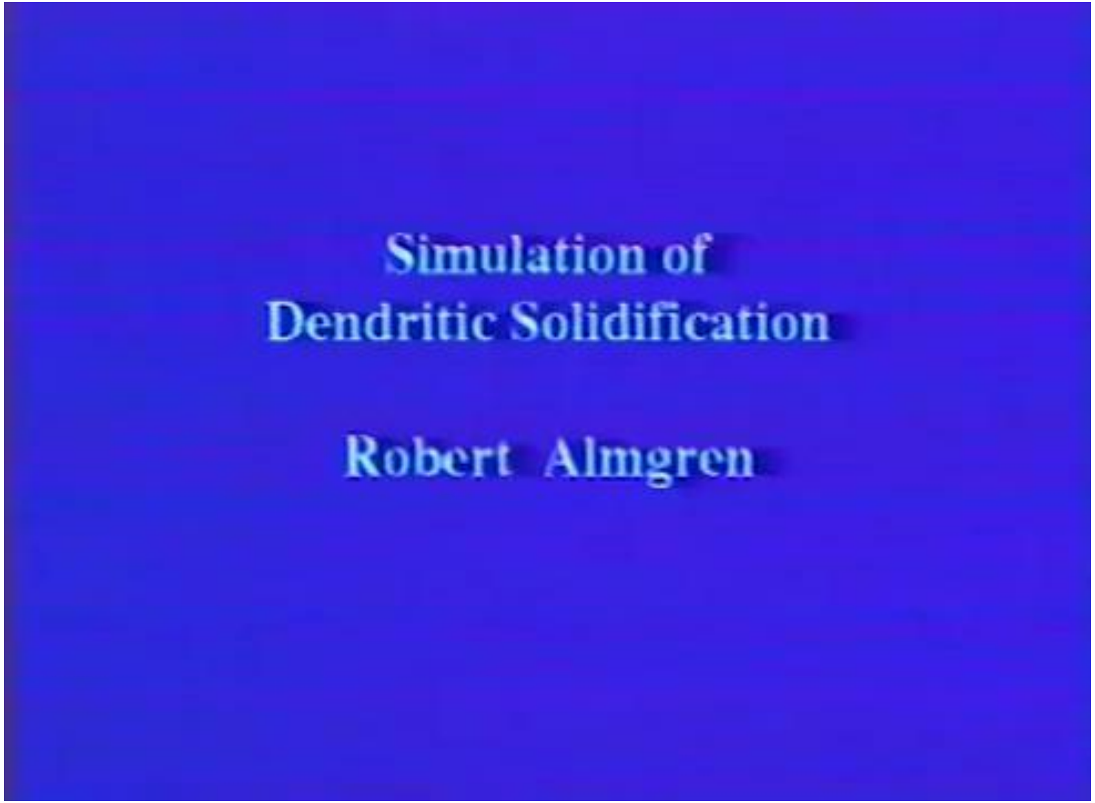
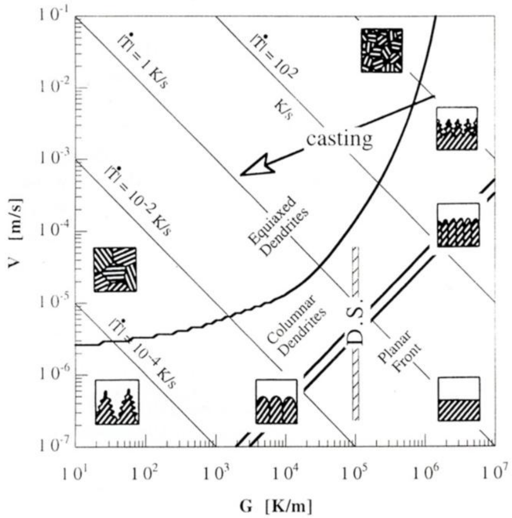


https://youtu.be/y46-IHG0OEg?si=ka-6Vn-J0LYr2fr3



Kurz, W., & Fisher, D. J. (1998). Solidification Microstructure: Cells and Dendrites. In *Fundamentals of Solidification* (pp. 80-87). Enfield, NH: Trans Tech Publications.

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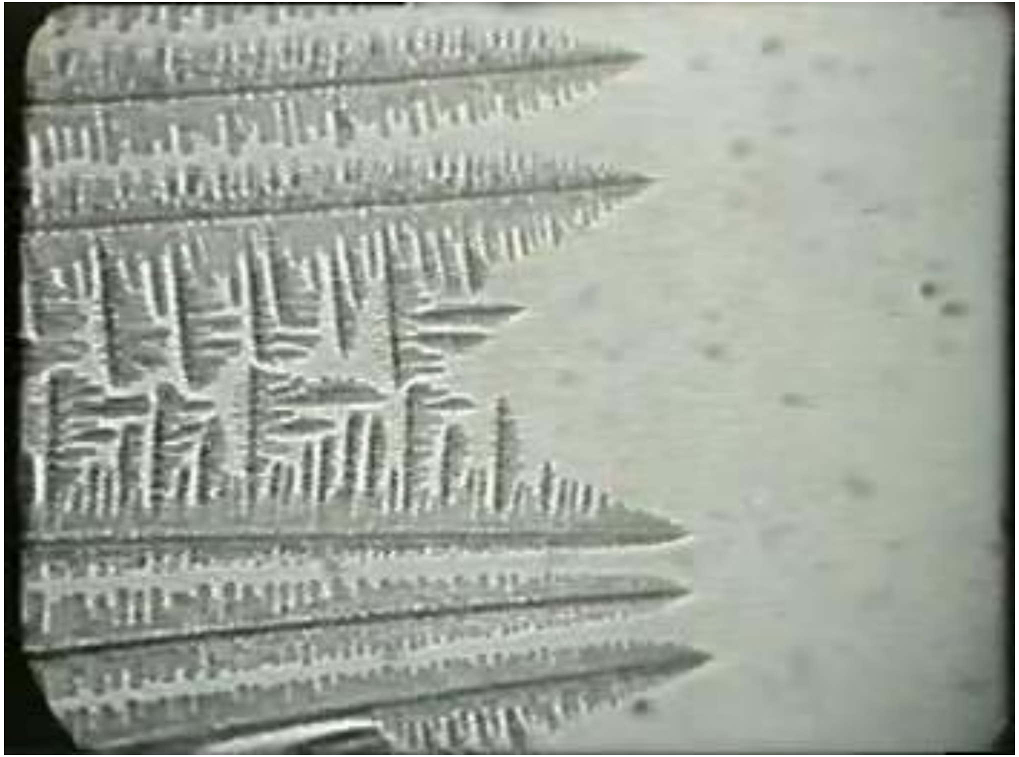
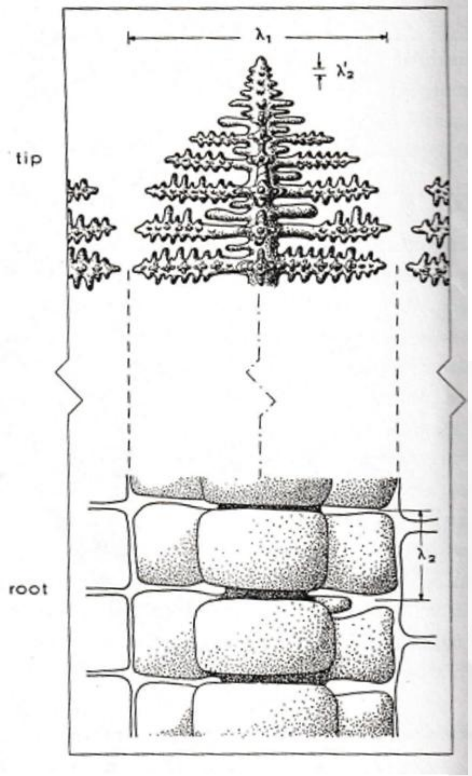
Dendritic growth





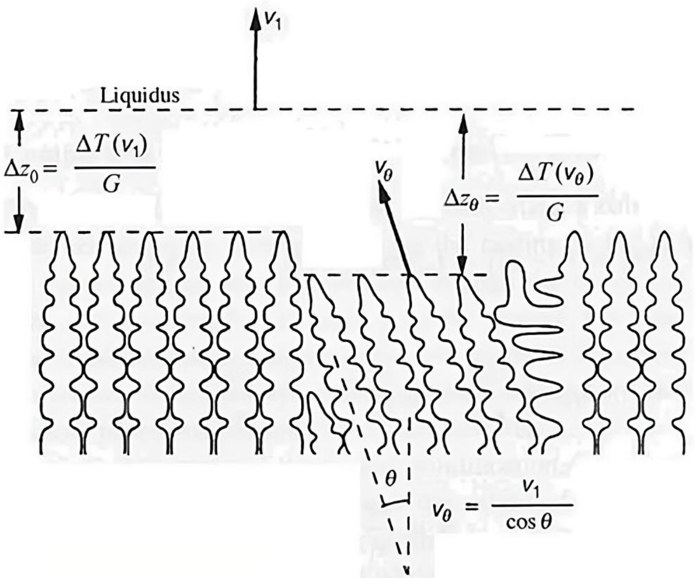
λ_1: Primary arm spacing

λ_2: Secondary arm spacing

Kurz, W., & Fisher, D. J. (1998). Solidification Microstructure: Cells and Dendrites. In *Fundamentals of Solidification* (pp. 80-87). Enfield, NH: Trans Tech Publications.

Dendritic growth (Grains)

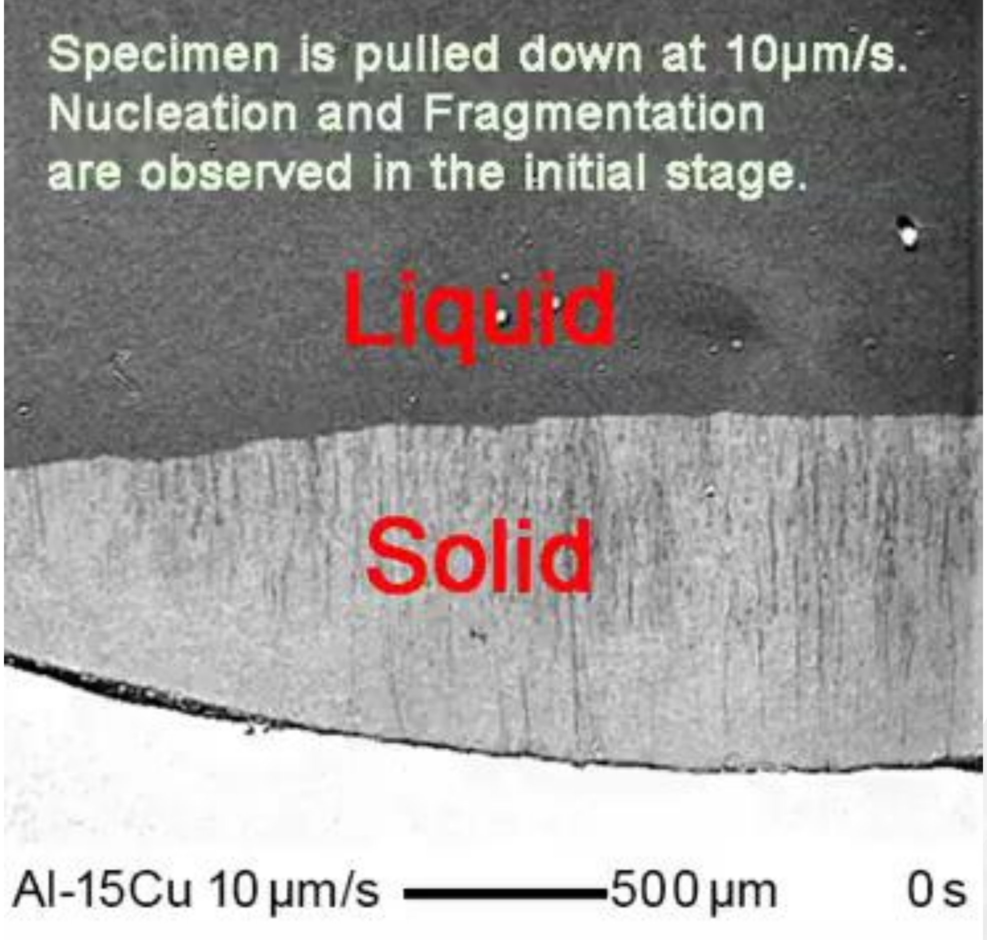
- Unfavorably oriented grain is eliminated
- Grain starts as cells then become crystals



R.C. Reed, The superalloys: Fundamentals and Application, Cambridge University Press, Cambridge, 2006.

Columnar to Equiaxed Transition

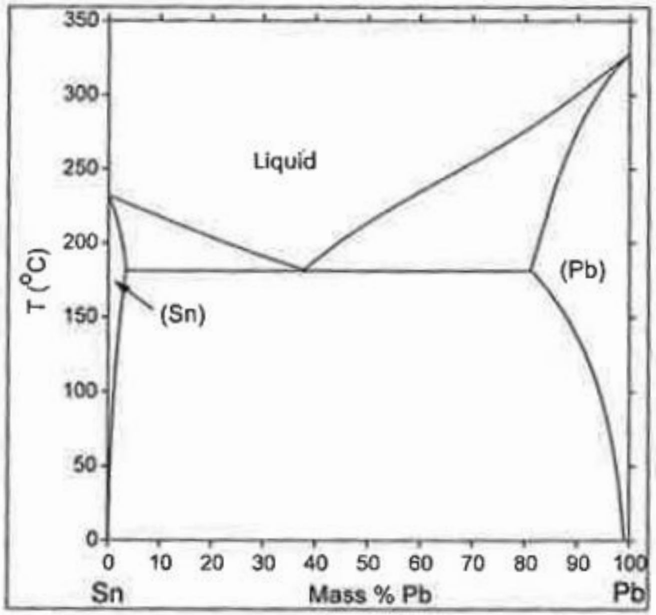
(CET)



https://youtu.be/LMqWWVzOMuA?si=h2uAsUyw7RMQmGzh

Eutectic, hypo and hyper-eutectic

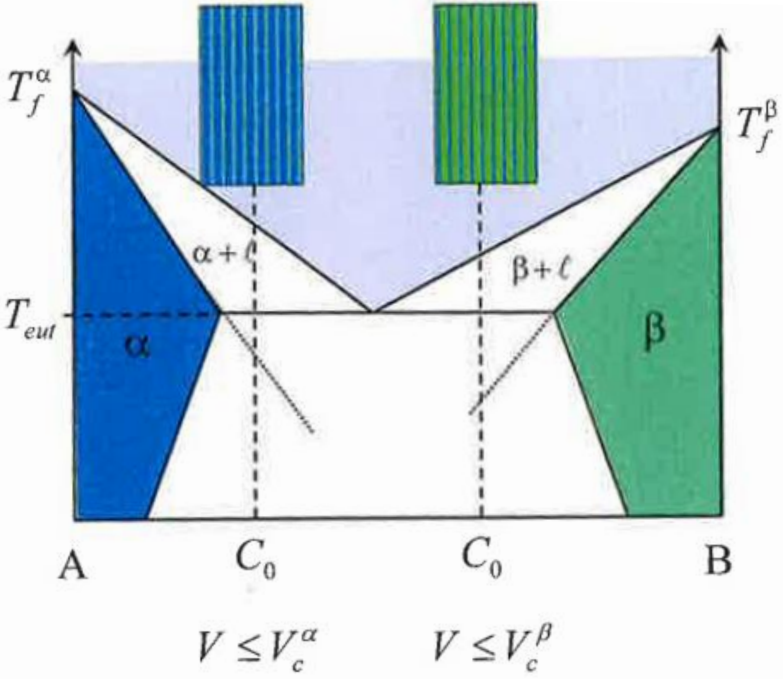
Eutectic



[Courtesy http:// www.metallurgy.nist.gov]

hypoeutectic

hypereutectic



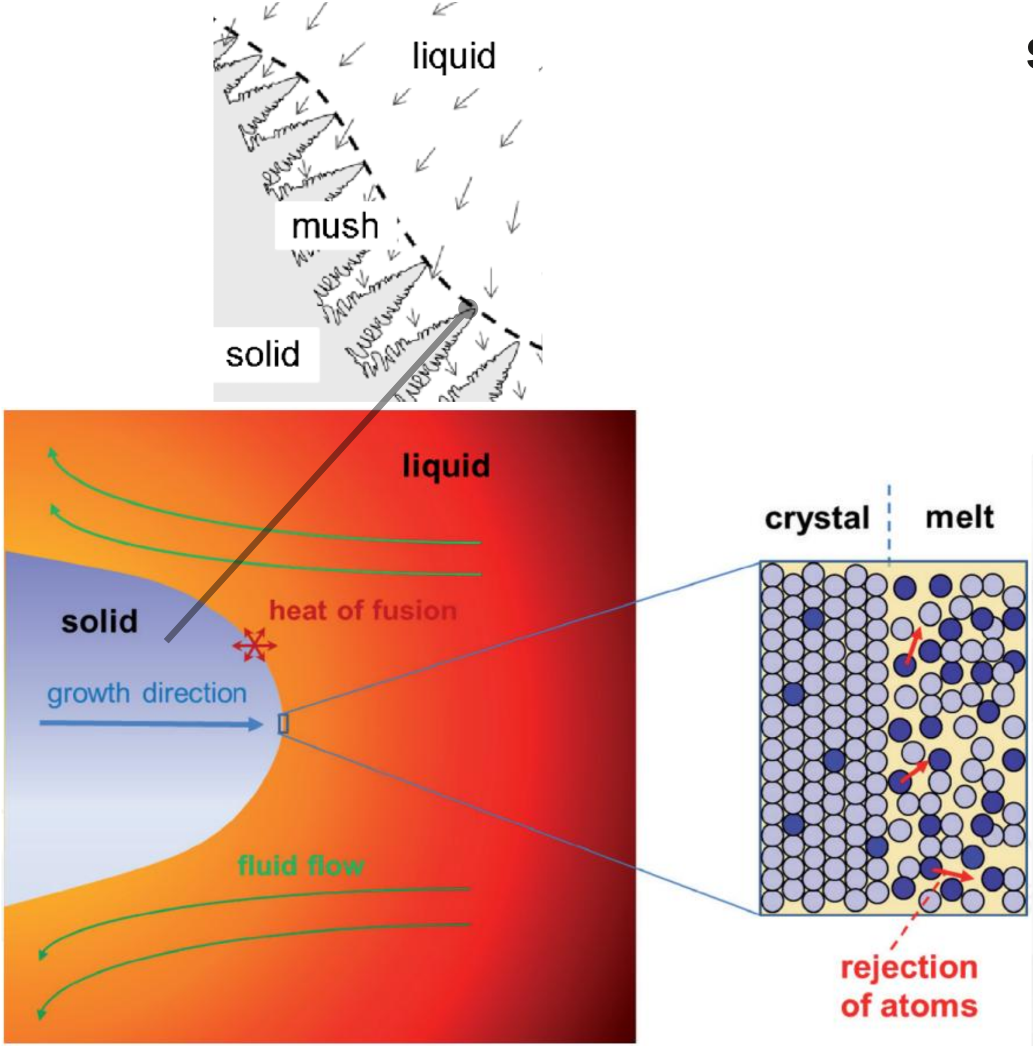
Eutectoid transformations

Martensite

Widmanstaetten ferrite

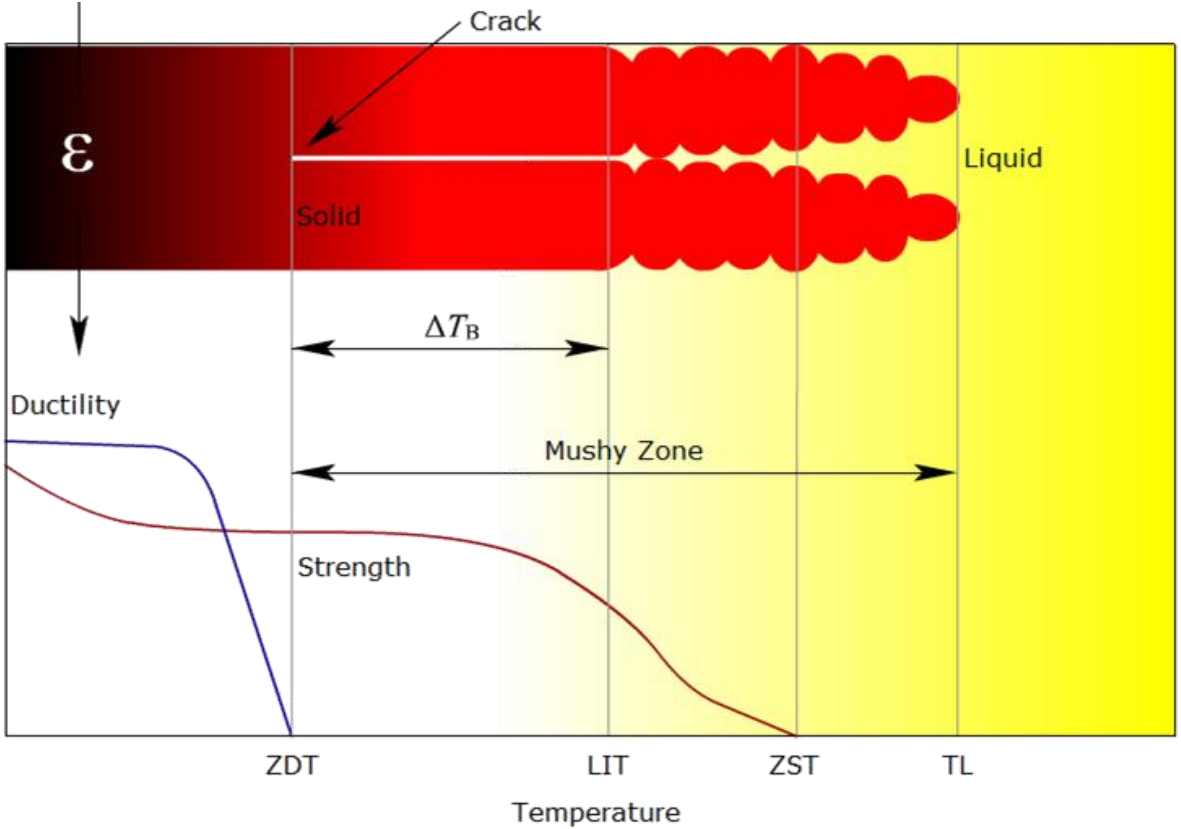
phase-trans.msm.cam.ac.uk

Segregation



Diefenbach, Angelika & Schneider, Stephan & Volkmann, Thomas. (2020). Experiment Preparation and Performance for the Electromagnetic Levitator (EML) Onboard the International Space Station. 10.5772/intechopen.93470.

Key temperatures during solidification



TL: Liquidus Temperature

ZST: Zero Strength Temperature

LIT: Liquid Impenetrable Temperature

ZDT: Zero Ductility Temperature

TS: Solidus

Segregation during solidification of a steel with nominal composition of C = 0.08%.

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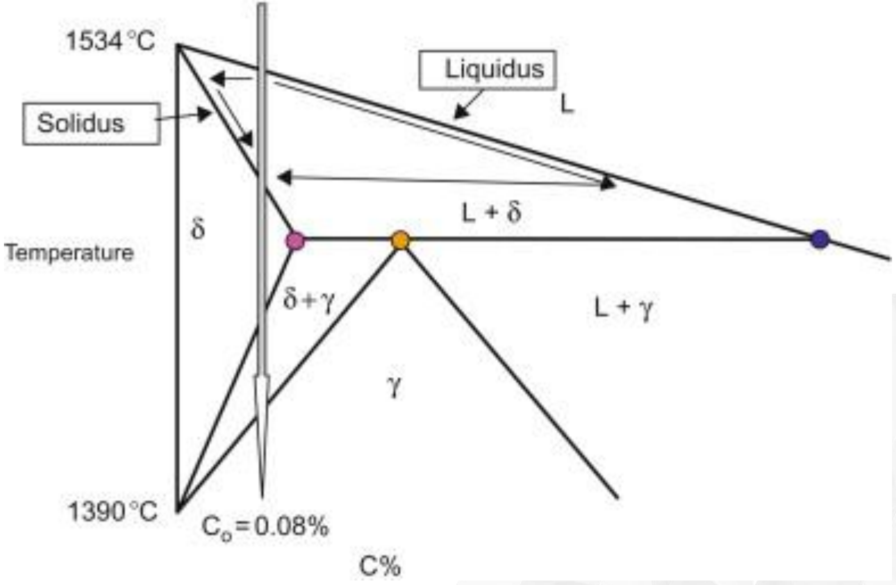
- The liquid concentration follows the liquid line in the phase diagram, and the solid concentration follows the solid line.
- At liquidus temperature, the melt composition is the nominal composition, but the composition of the final melt is high.
- At liquidus, the solid dendrite tip has a lower concentration, but it is increasing when the solidification continues.
- **This segregation is called microsegregation.**
- If the diffusion is infinite, the concentration at solidus when all the melt has been solidified is homogenous again and the composition is equal to the nominal composition.
- In reality, the diffusion is not infinite and so some small composition gradients typically exist after the solidification.
- If the microsegregation is serious, it can lead to hot cracking, to formation of inclusions, and eventually to macrosegregations.



Seppo Louhenkilpi, Chapter 1.8 - Continuous Casting of Steel, Editor(s): Seshadri Seetharaman, Treatise on Process Metallurgy, Elsevier, 2014, Pages 373-434, ISBN 9780080969886

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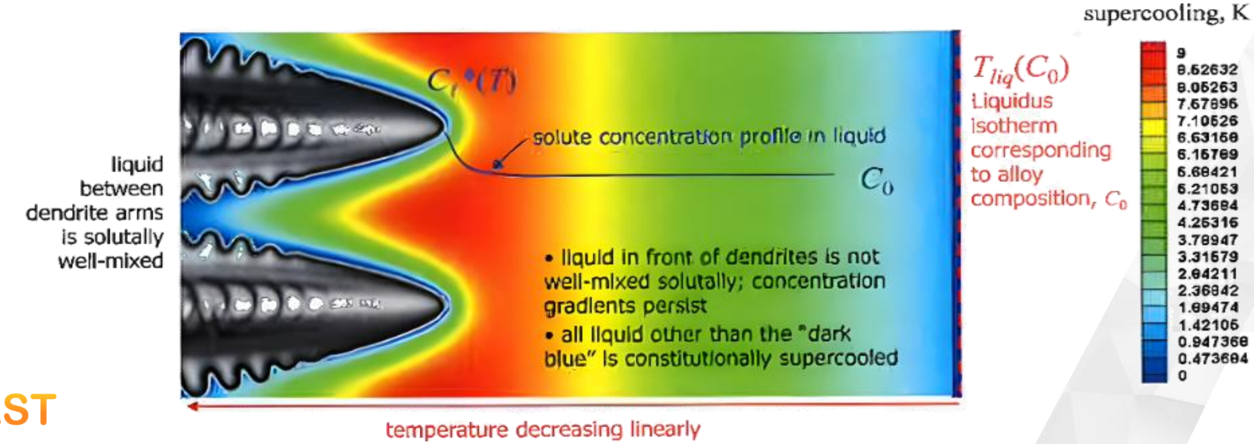
Back diffusion effects

SWERIM

- Back diffusion is the process of **solute atoms diffusing back into the solid from the liquid during solidification**.
- This happens as the solid-liquid interface moves, and it works to homogenize compositional differences within the solidified material.
- Back diffusion reduces microsegregation and leads to a final solidified structure that is closer to equilibrium compared to models that neglect solid-state diffusion, like the classic Scheil model.



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Limiting cases

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- Lever rule (equilibrium solidification model): complete mixing of solute in liquid and solid is assumed

$$f_s = \frac{1}{1-k_0}\frac{T_\ell - T}{T_m - T};\ T_s \le T \le T_\ell \qquad k_0 = \frac{C_s}{C_\ell}$$

- Scheil model: complete mixing of solute in liquid and no mixing of solute in solid is assumed

$$f_s = 1 - \left(\frac{T_m - T}{T_m - T_\ell}\right)^{\frac{1}{k_0 - 1}};\ T_s \le T \le T_\ell$$

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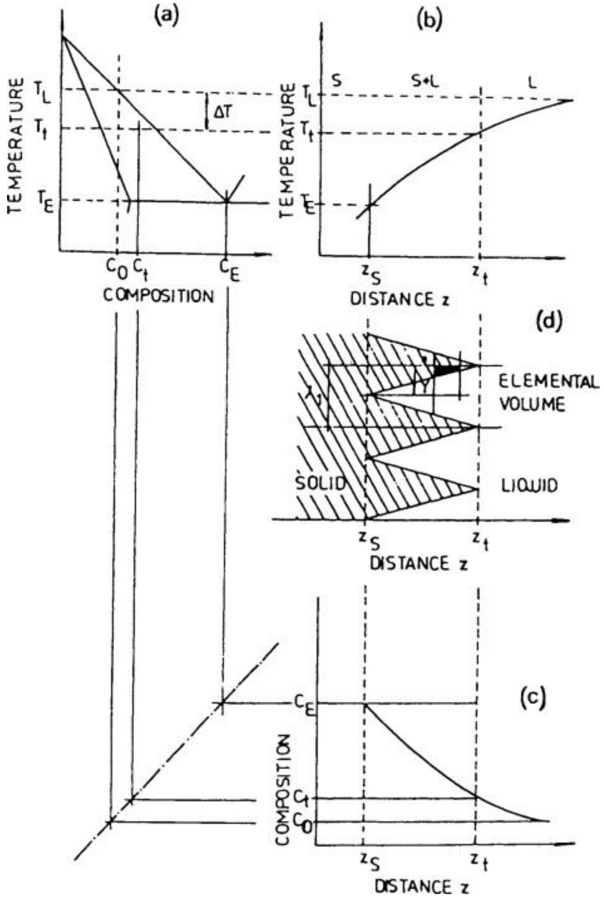
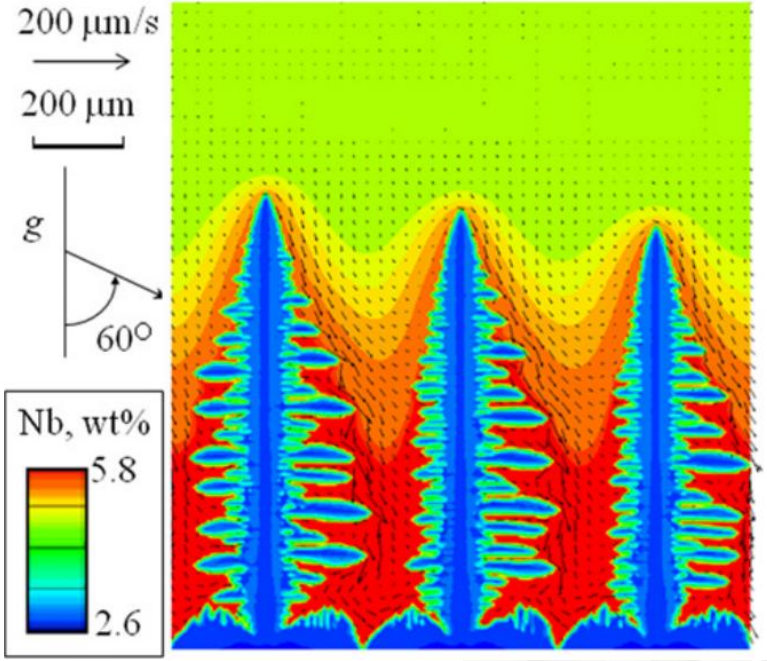
Segregation during solidification of a steel with nominal composition of C = 0.08%.





Yuan, Lang & Lee, Peter. (2010). Dendritic solidification under natural and forced convection in binary alloys: 2D versus 3D simulation. Modelling and Simulation in Materials Science and Engineering.

Physical Metallurgy. Fourth Edition • 1996. Edited by Robert W. CAHN and Peter HAASEN

Micro-segregation

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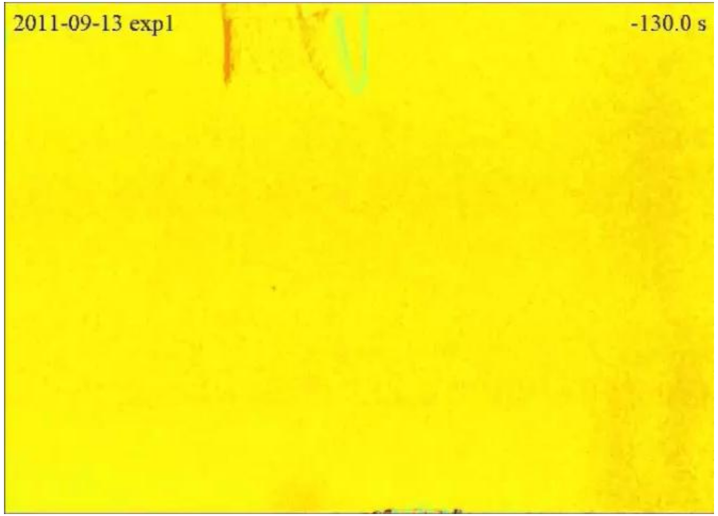
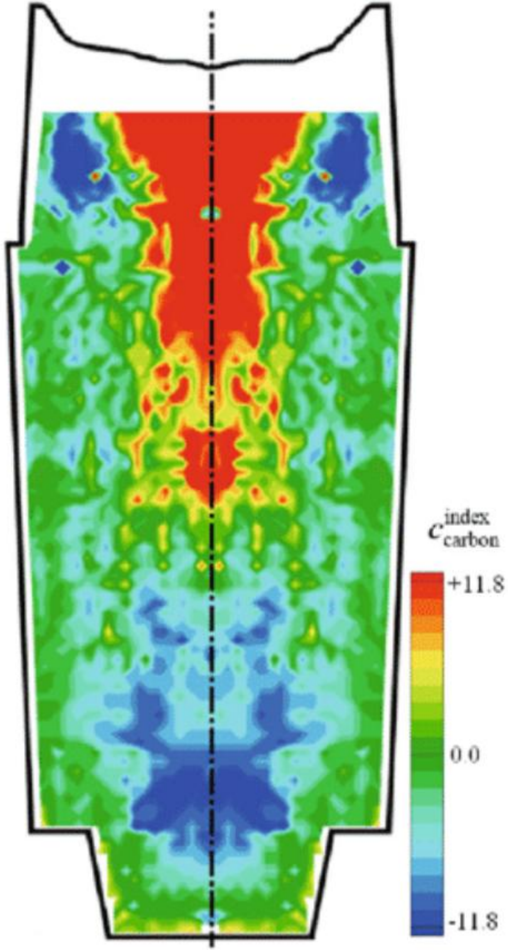
- Microsegregation occurs since the solid forming is different in composition from the liquid from which it forms (generally less rich in solute).

- The excess solute is thereby rejected into the liquid, into the narrow spaces between the dendrite arms.



N. Shevchenko, O. Roshchupkina, O. Sokolova, S. Eckert, "The effect of natural and forced melt convection on dendritic solidification in Ga–In alloys", Journal of Crystal Growth, Volume 417, 2015, Pages 1-8, ISSN 0022-0248,



Duan, Z., Tu, W., Shen, B. *et al.* Experimental Measurements for Numerical Simulation of Macrosegregation in a 36-Ton Steel Ingot. *Metall Mater Trans A* **47**, 3597–3606 (2016).

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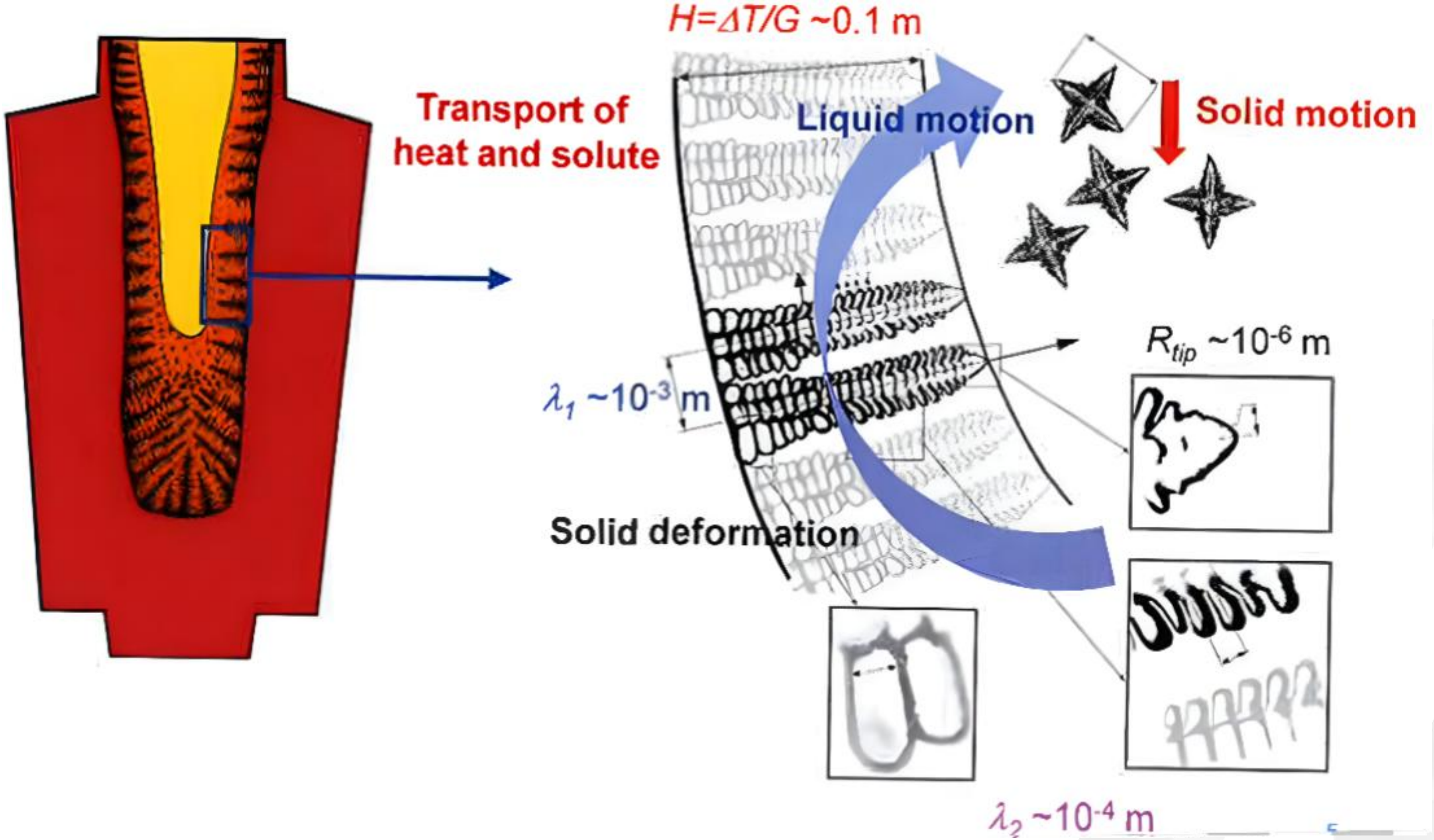
Ingot example



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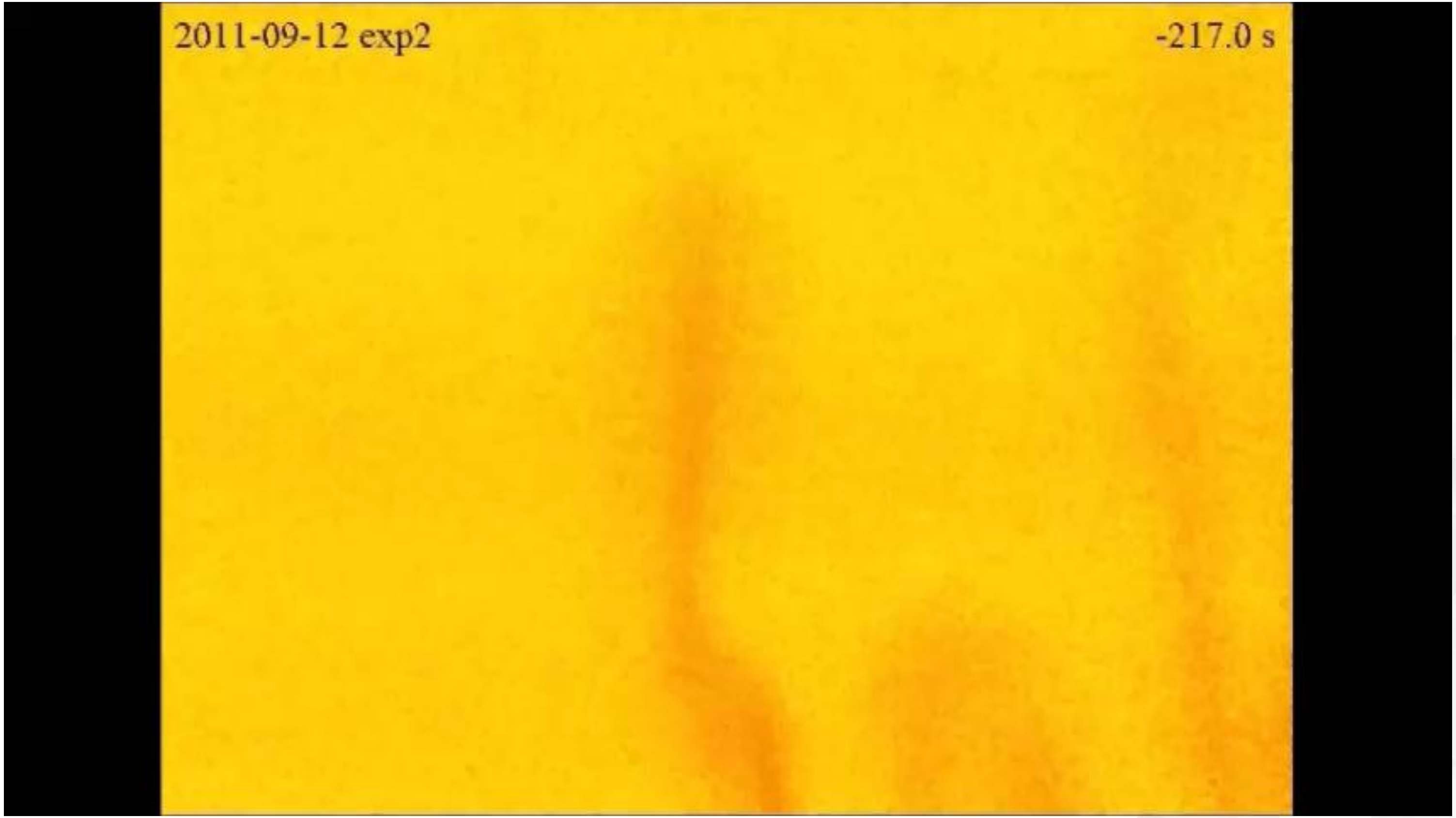
Segregation effects



Courtesy of N. Shevchenko. More info in: N. Shevchenko, O. Roshchupkina, O. Sokolova, S. Eckert, “The effect of natural and forced melt convection on dendritic solidification in Ga–In alloys”, Journal of Crystal Growth, Volume 417, 2015, Pages 1-8, ISSN 0022-0248,

Summary solidification

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CET

- Columnar grains are favoured if G/vT is large (reduced zone of undercooled liquid ahead of dendrite tips)
- An increasing growth restriction factor, (m,co,i(1-k))/D;, promotes the formation of equiaxed grains. It also reduces the size of equiaxed grains (larger undercooling for same velocity).
- Convection favours the formation of equiaxed grains (dendrite arm detachment)
- Increasing cooling rate reduces the size of equiaxed grains(deeper "exploration" of nucleation sites distribution)

Equiaxed

- Small grains tend to be globulitic, large ones to be dendritic(competition of growth between the envelope of the grains and the solid inside)

Columnar

- Grain motion affects the shape of the mushy zone. Evolution of grain texture and transverse grain size in columnar zone can only be predicted with the help of advanced models (CAFE, phase-field, ...)

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Ingot casting experiment

Ingot casting

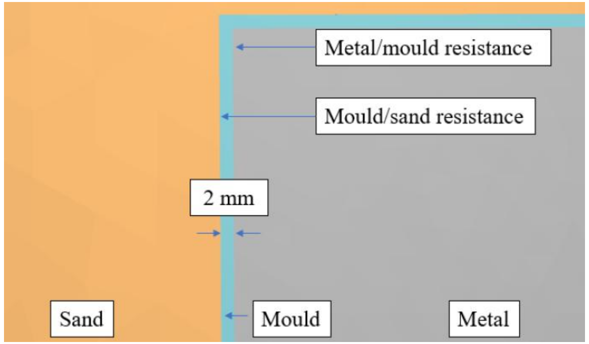
- During steel material development, its crucial to understand the solidification behaviour during casting.
- Pilot scale experiments carried out at Swerim to replicate industrial processes.

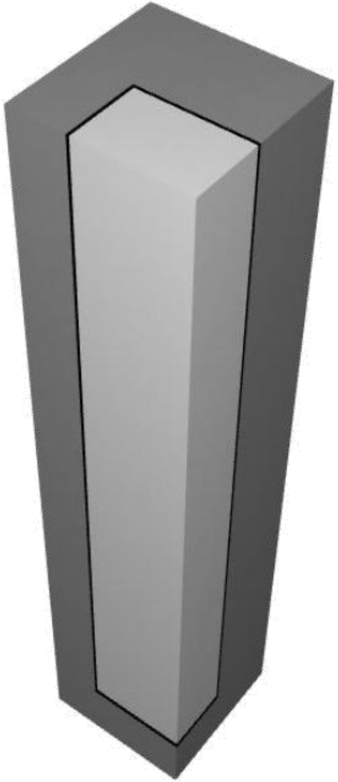
Courtesy of Uddeholm AB

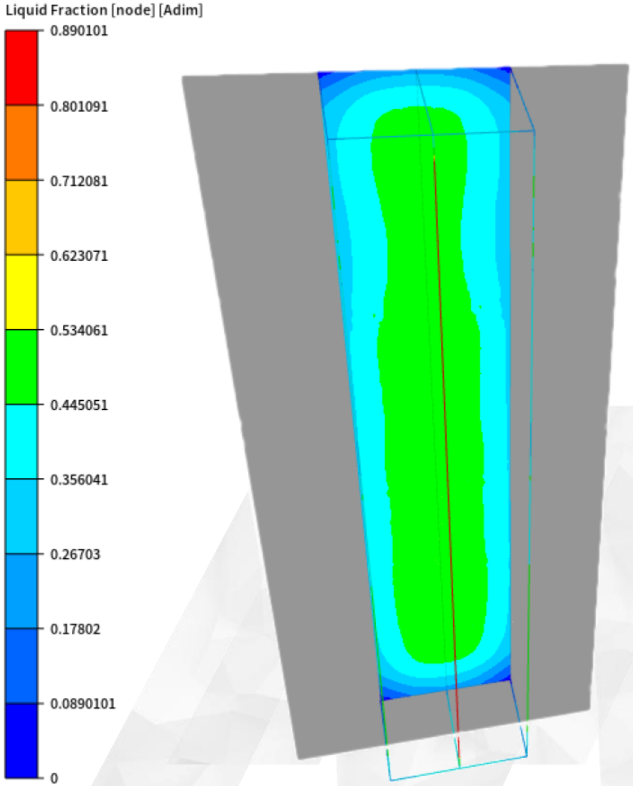
Pilot trial

Numerical model

- The ingot and sand mould geometry included in the model
- The boundary condition selected
- Output in terms of solidification and cooling rate obtained



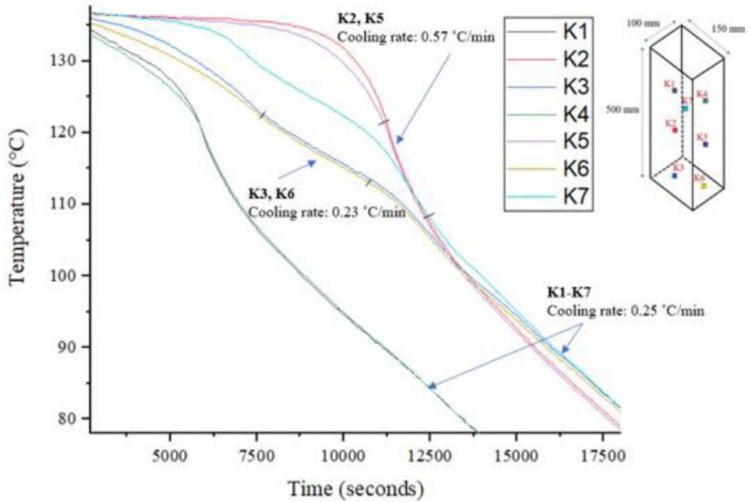


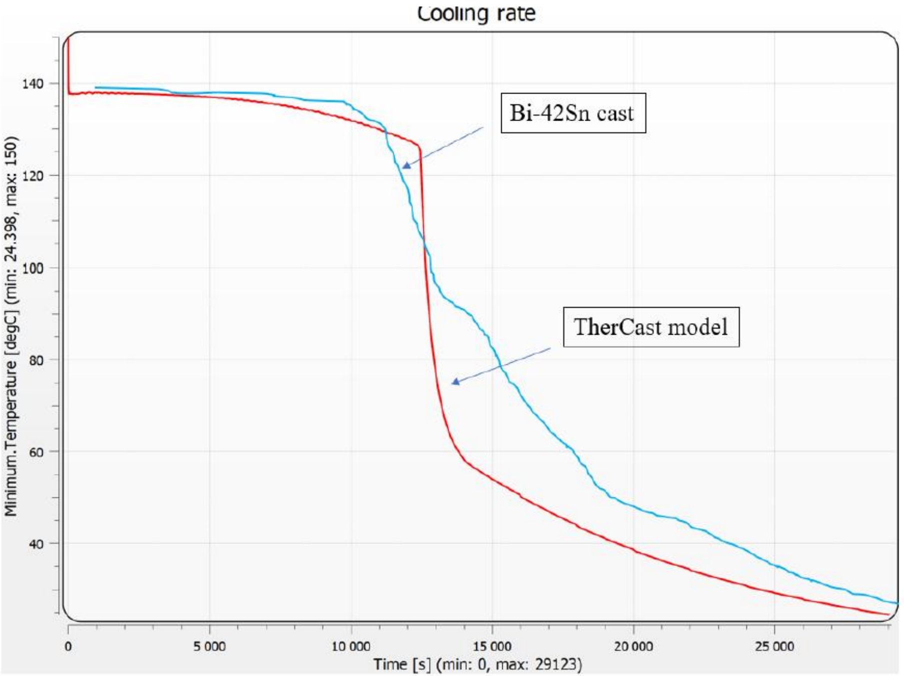


Hedman, D. (2020). Casting and Characterization of Advanced High Strength Steels (MSc Dissertation). LTU

Model vs Pilot test

- Cooling rate from pilot trial and model compared.
- Model verified and could be used for other steel grades.





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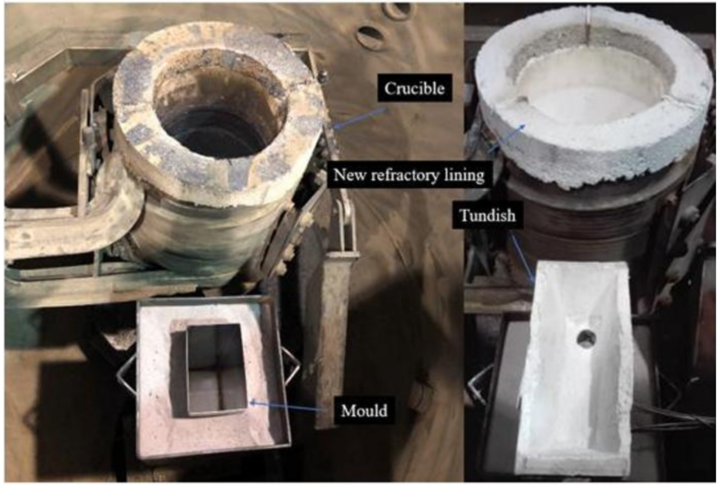
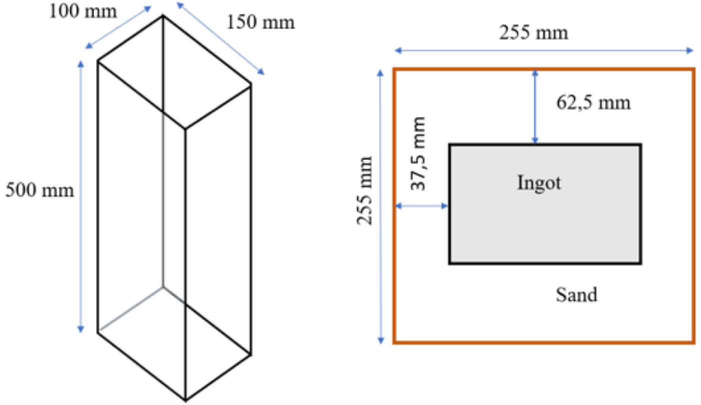
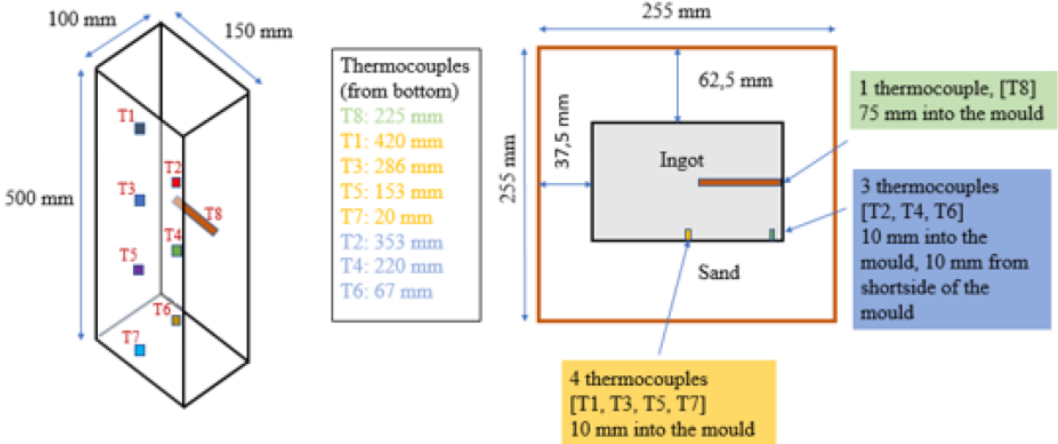
Setup

SWERIM

- Ingot and sand box size selected.
- Thermocouples placed in locations of interest.







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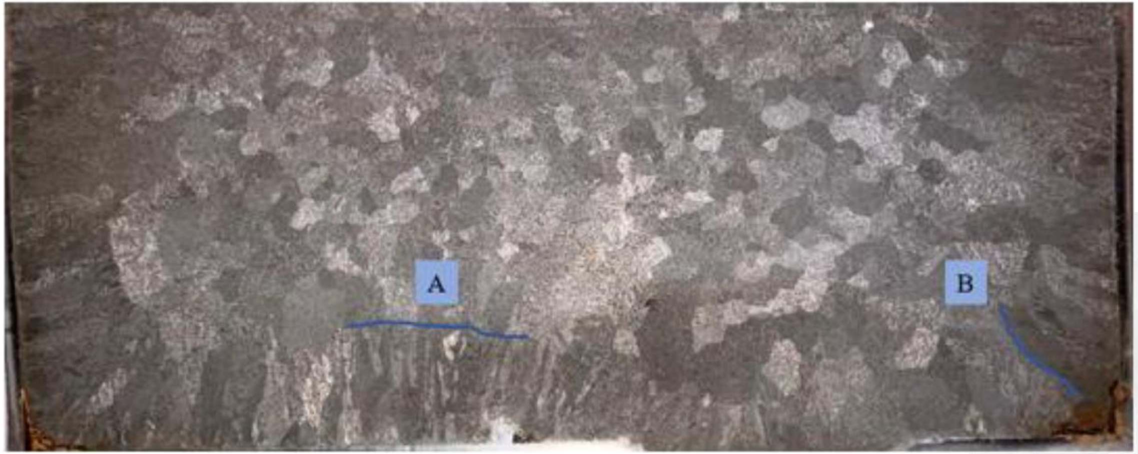
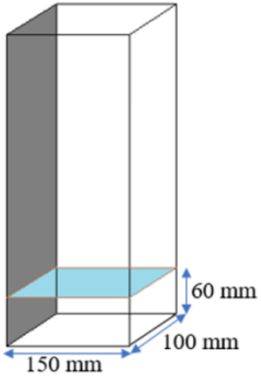
Pilot test - steel

- Pilot test with steel grade tested.





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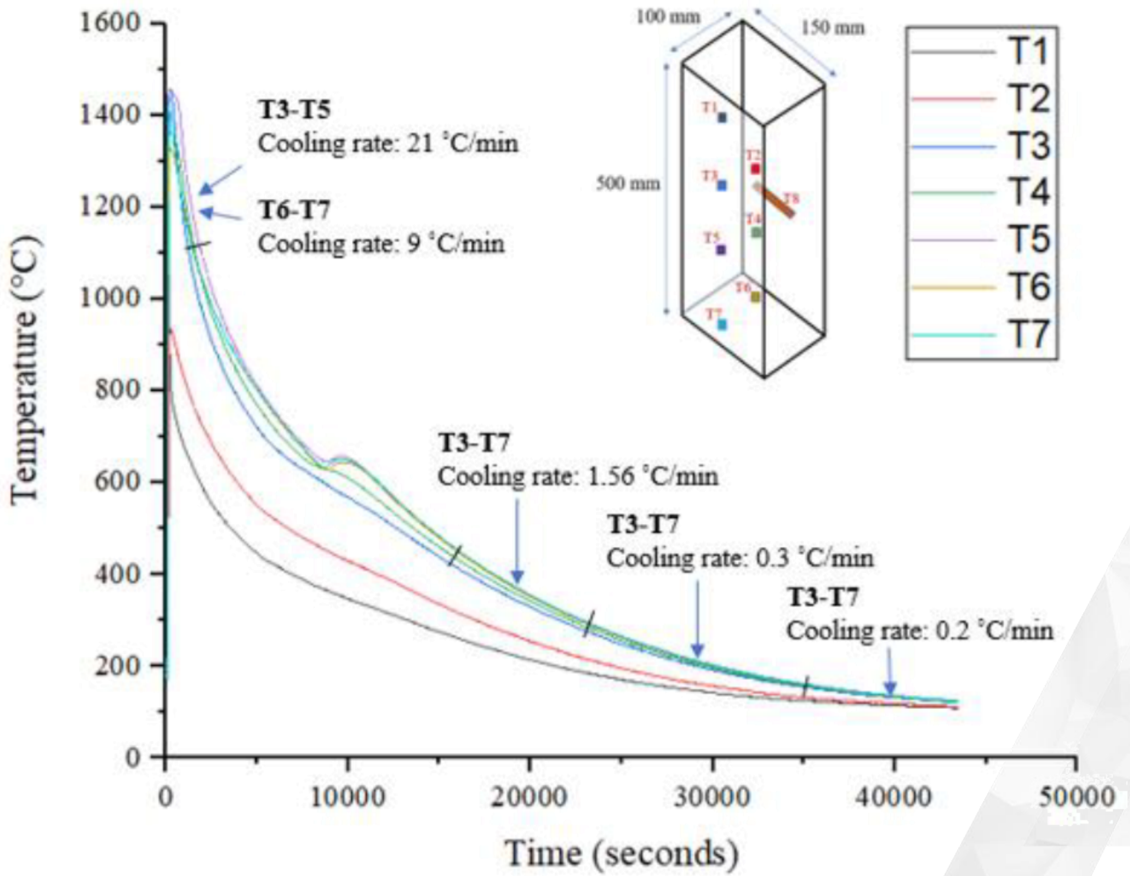
Pilot test - steel



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