Lecture 5: Casting and metal Injection Molding

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EPFL

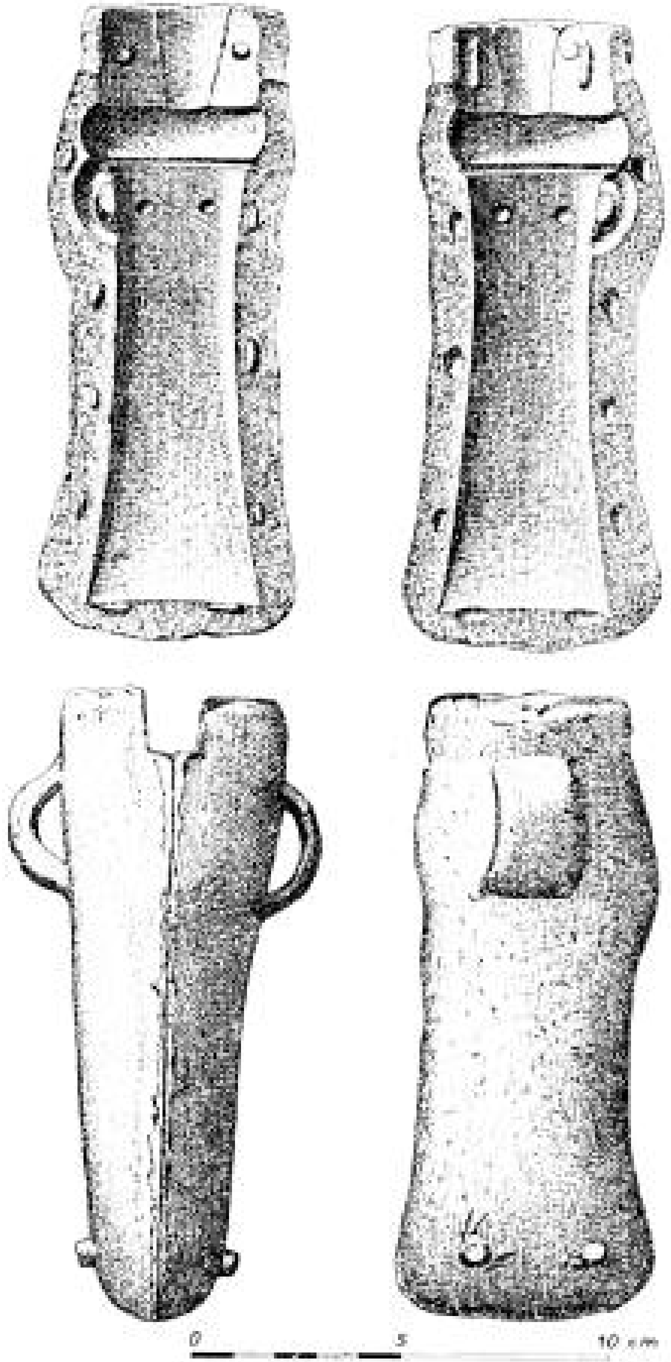
Learning objectives

- Introduction / *'From bronze age axes to car engine'* : a long history…
- Casting processes / Description
  - Sand casting
  - Lost-wax casting ('cire perdue')
  - Die casting
  - Metal-injection-molding
- Physics and metallurgy of casting
- Micro-casting

Casting: from the Bronze age...

(from ~ – 3000 BC to ~ - 1000 BC)

Hénon, Côte d'Armor, Brittany (Bronze age)

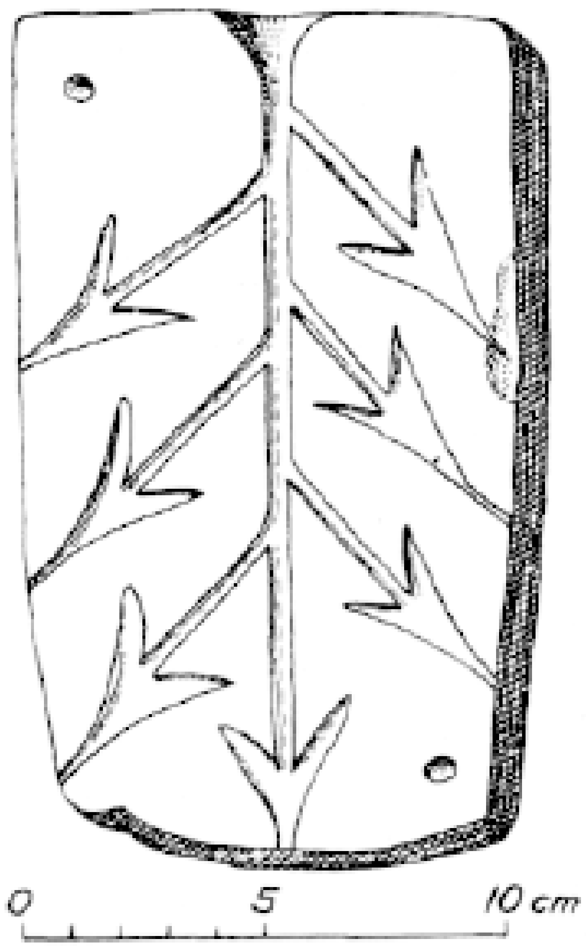


Mold for a bronze age Axe
(Cachette d'Azay-le-rideau)

From: Cordier Gérard. Quelques moules de l'Age du Bronze provenant de la Touraine et du Berry. In: Bulletin de la Société préhistorique de France, tome 59, n°11-12, 1962. pp. 838-849)

Metal: Bronze (Copper / 85.2%, Tin / 10.2%, Antimony / 2.8%, Lead / 1.8 %)

Casting: from the bronze age...



‘Moules pour sept pointes à fondre d’un jet’ - Corcellettes, rive ouest du Lac de Neuchâtel / Grandson

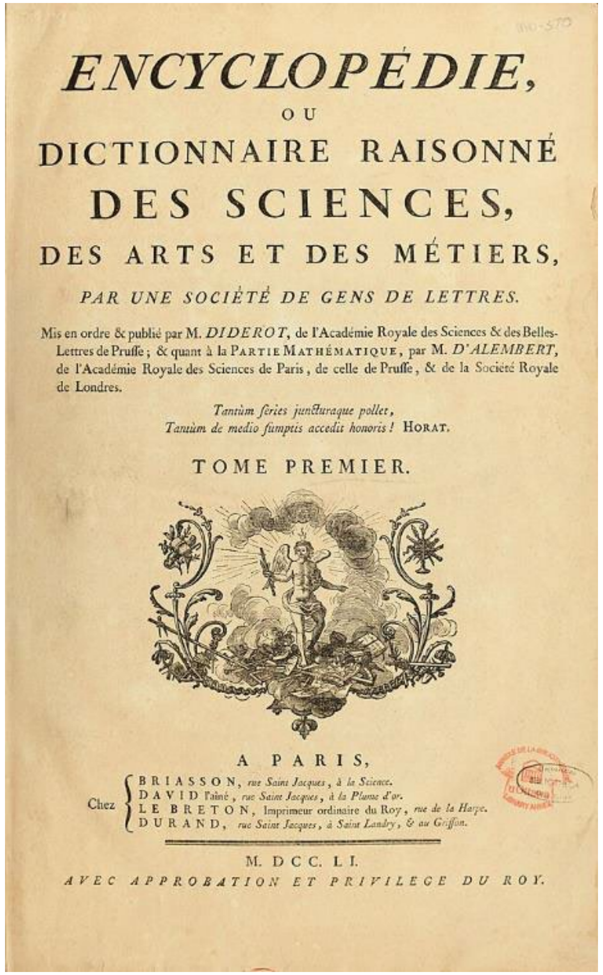
(From B. Van Muyden and A. Colomb, ‘Musée cantonal Vaudois: antiquités lacustres’, Album Lausanne, 1896)

Final bronze age (1550-1200 BC).

Casting: a long history...

Benvenuto Cellini : Perseus (~ 1545)

Casting: a long history…


ENCYCLOPÉDIE,
OU
DICTIONNAIRE RAISONNÉ
DES SCIENCES,
DES ARTS ET DES MÉTIERS,
PAR UNE SOCIÉTÉ DE GENS DE LETTRES.

Mis en ordre & publié par M. DIDEROT, de l'Académie Royale des Sciences & des Belles-Lettres de Pruſſe; & quant à la PARTIE MATHÉMATIQUE, par M. D'ALEMBERT, de l'Académie Royale des Sciences de Paris, de celle de Pruſſe, & de la Société Royale de Londres.

Tantùm ſeries juncturaque pollet,
Tantùm de medio ſumptis accedit honoris! HORAT.

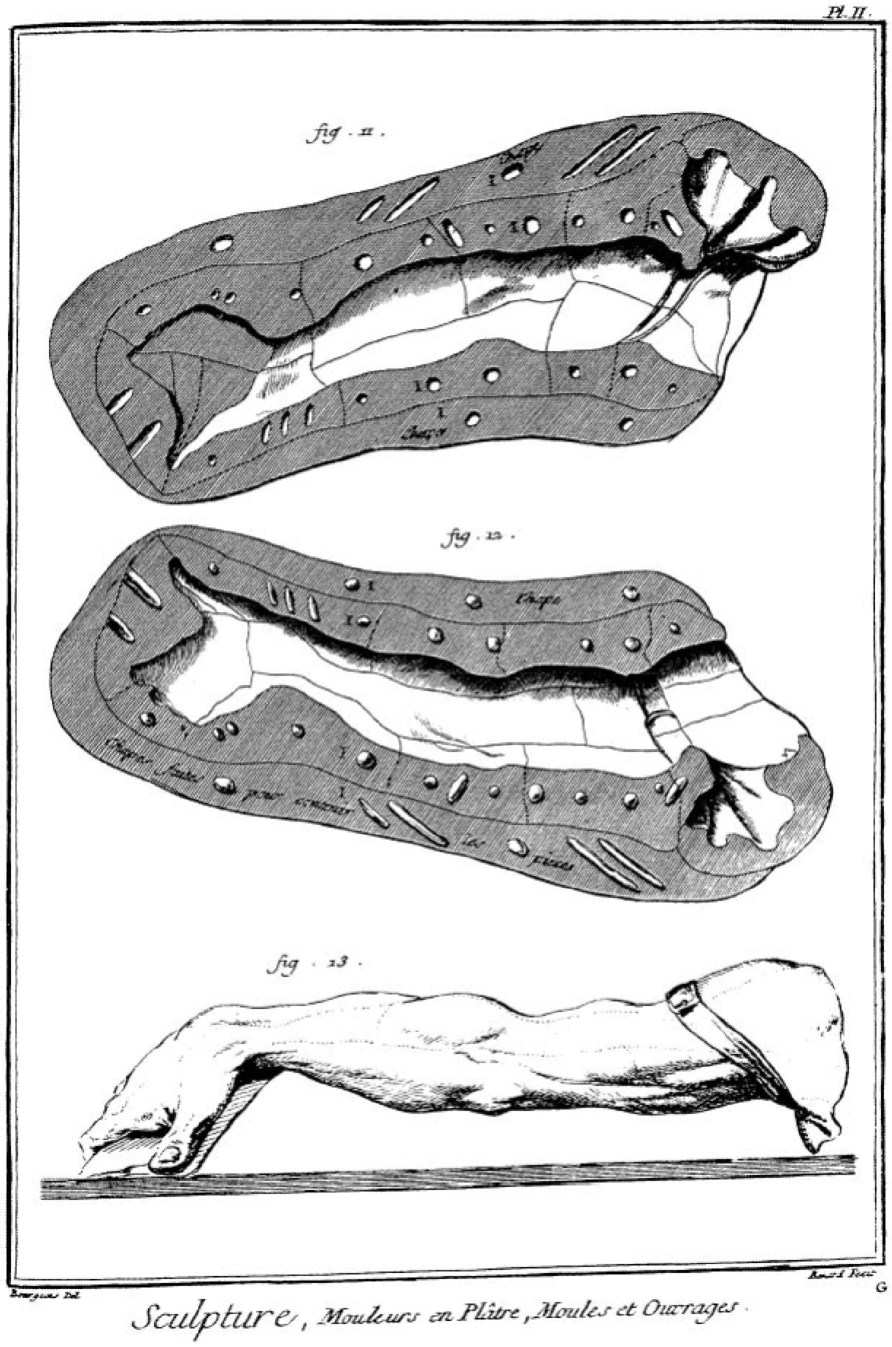
TOME PREMIER.

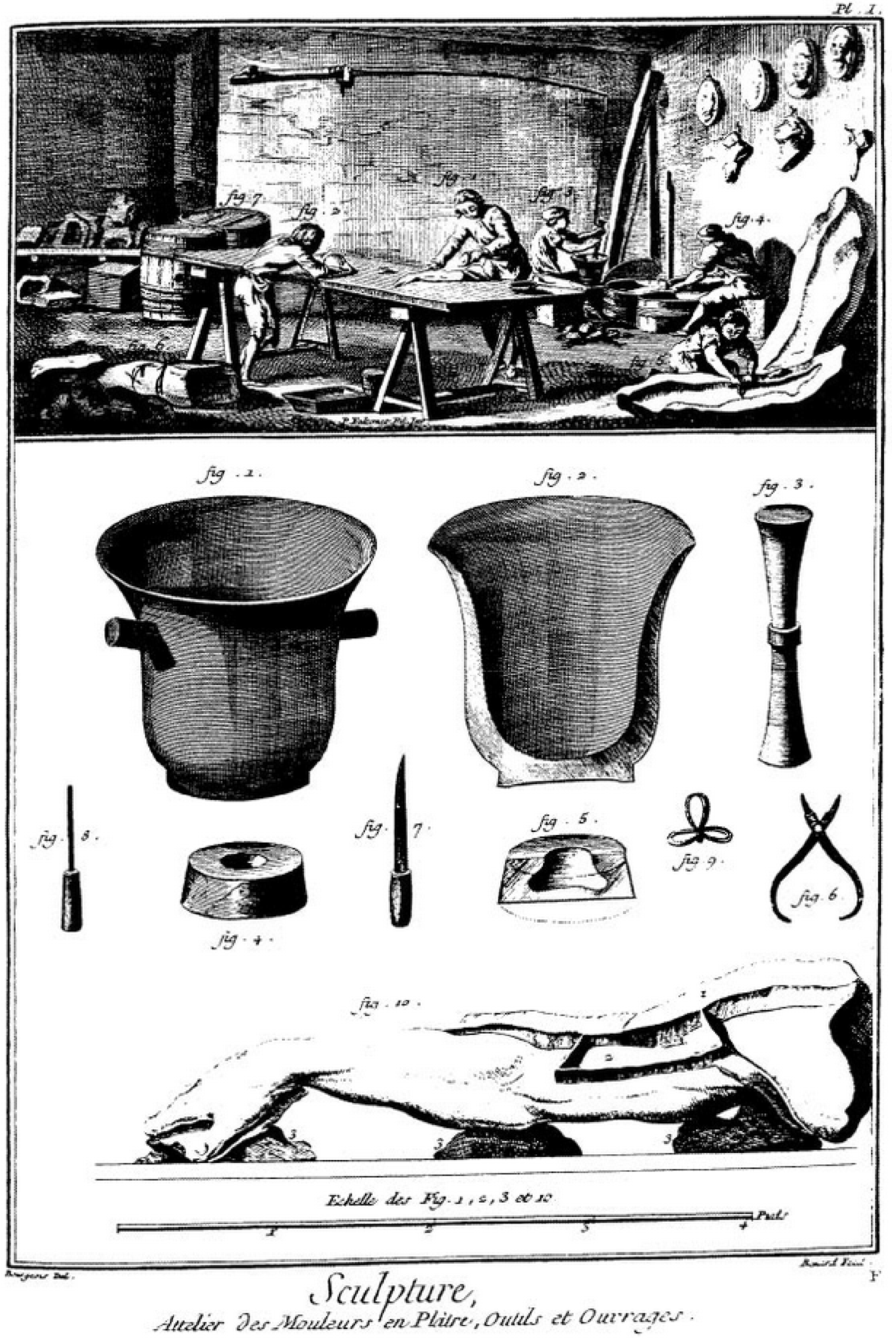
A PARIS,

Chez BRIASSON, rue Saint Jacques, à la Science.
DAVID l'aîné, rue Saint Jacques, à la Plume d'or.
LE BRETON, Imprimeur ordinaire du Roy, rue de la Harpe.
DURAND, rue Saint Jacques, à Saint Landry, & au Griffon.

M. DCC. LI.

AVEC APPROBATION ET PRIVILEGE DU ROY.



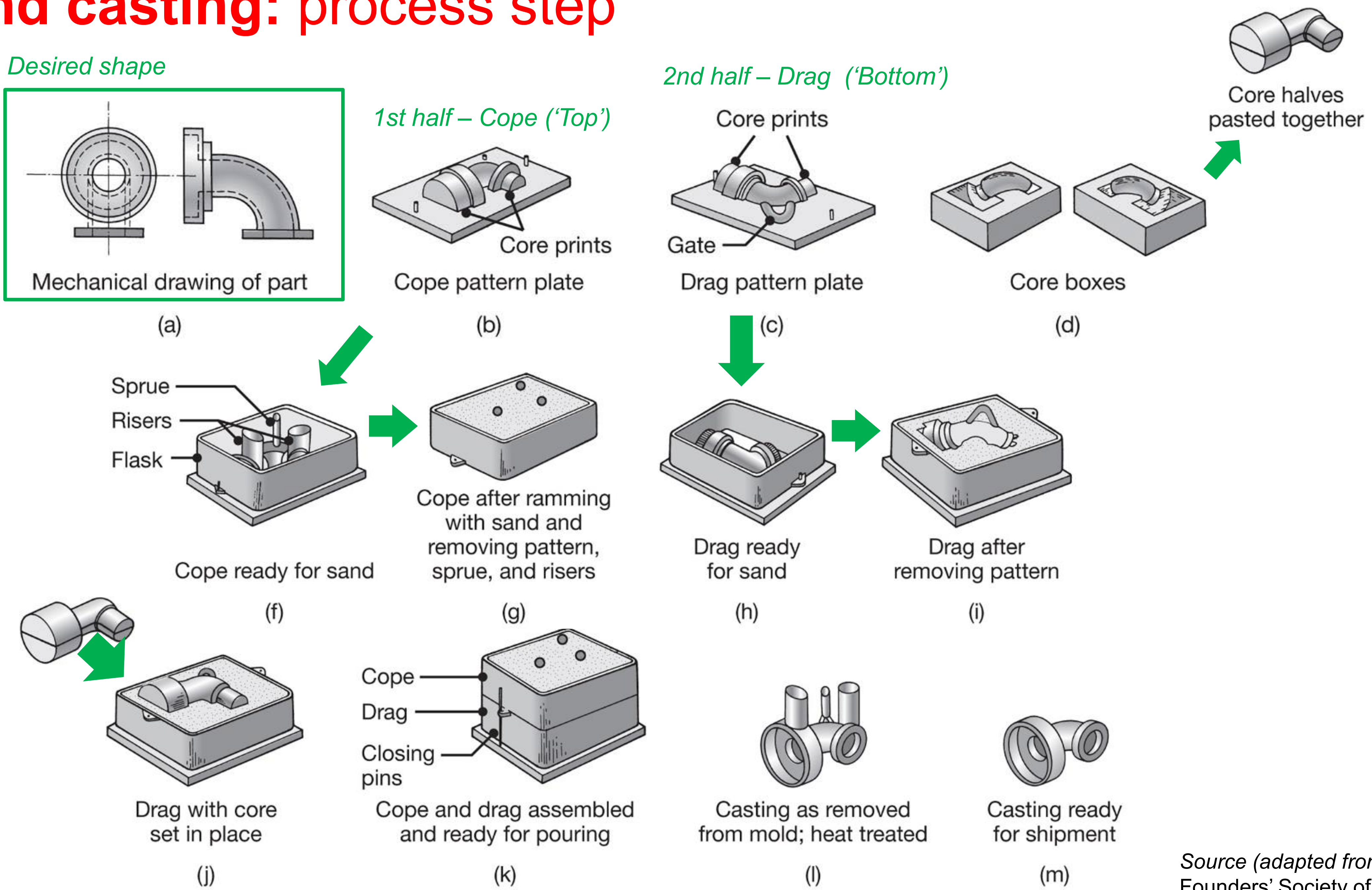


Encyclopédie de Diderot-d'Alembert (1757)

Casting processes in modern days

- Sand casting
- Lost-wax casting (‘cire perdue’)
- Die casting
- Metal injection molding

Sand casting: process step

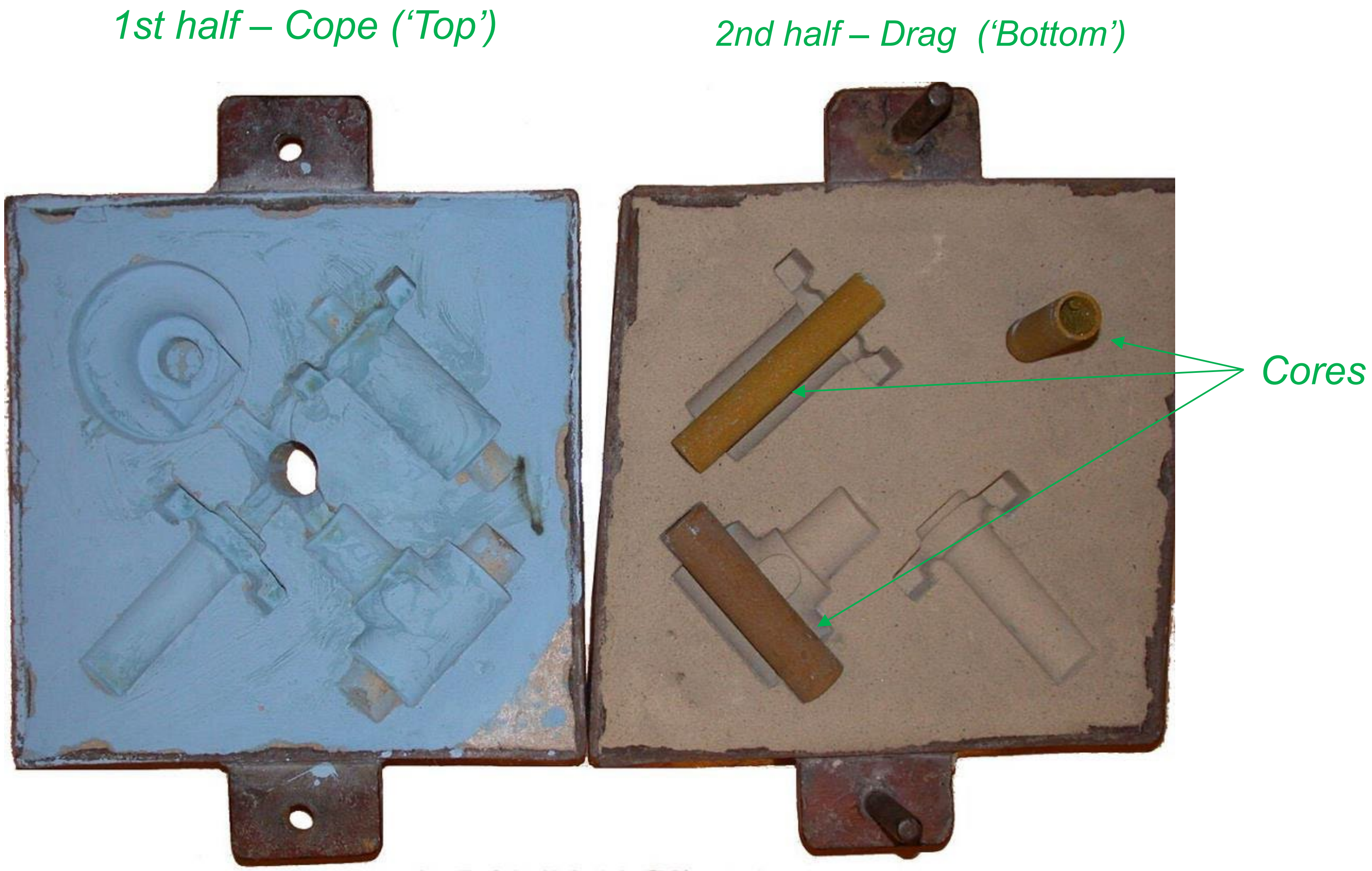


Source (adapted from): Steel Founders' Society of America.

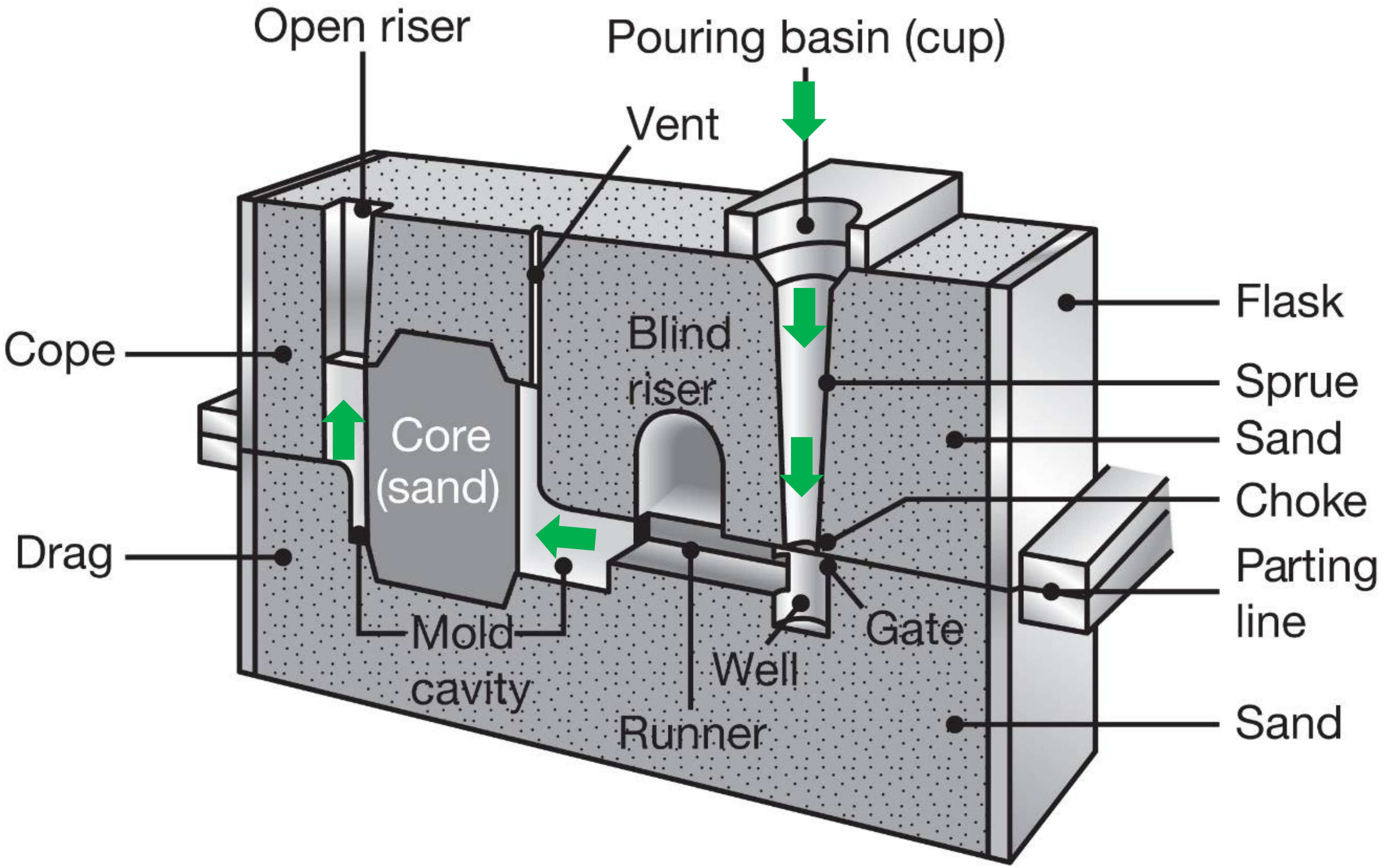
Sand casting

- Illustrative interesting didactical videos:
  - Car engine block fabrication: https://youtu.be/211Xkut0VGI
  - Car engine (BMW) Industry: https://youtu.be/N2hYTdrzujI

Illustration



Sand casting mold: a typical configuration



Why ‘sand’?

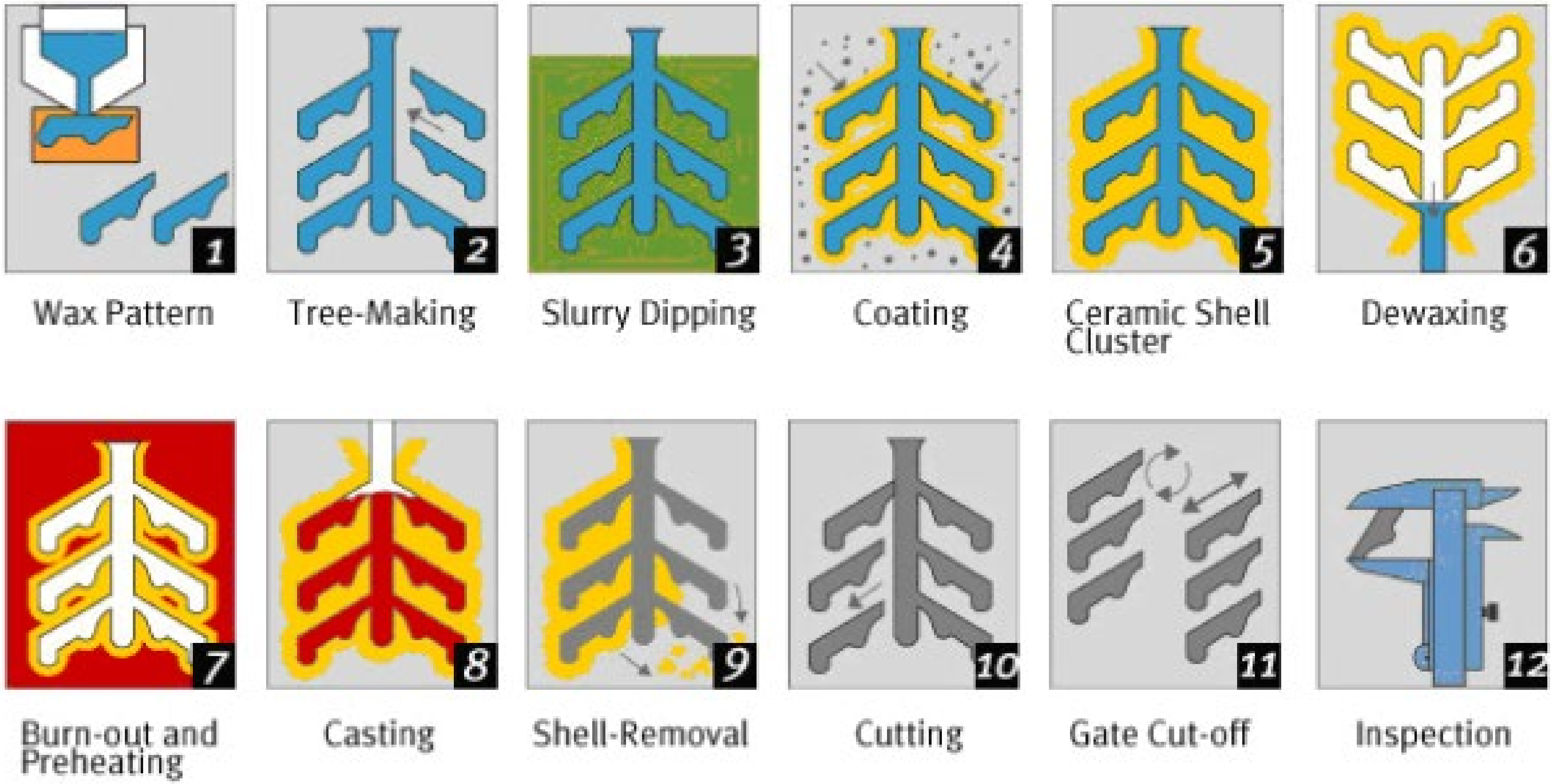
(Discussion in class)

1. **Refractory** material (low conductivity)
2. **Permeable to gas**
3. Thermally **stable**
4. Do not degrade when the metal shrink
5. Can be removed easily
6. Reusable

- ‘Green sand casting’
  - Use of a mix of natural sand, clay and water
  - Compacted

Lost-wax casting ('Cire perdue')

- Also called 'Investment casting'



Working principle: https://youtu.be/33p0Nih6YkY
La même... En Français: https://youtu.be/wJJMc9NUPO4

Other methods: centrifugal casting

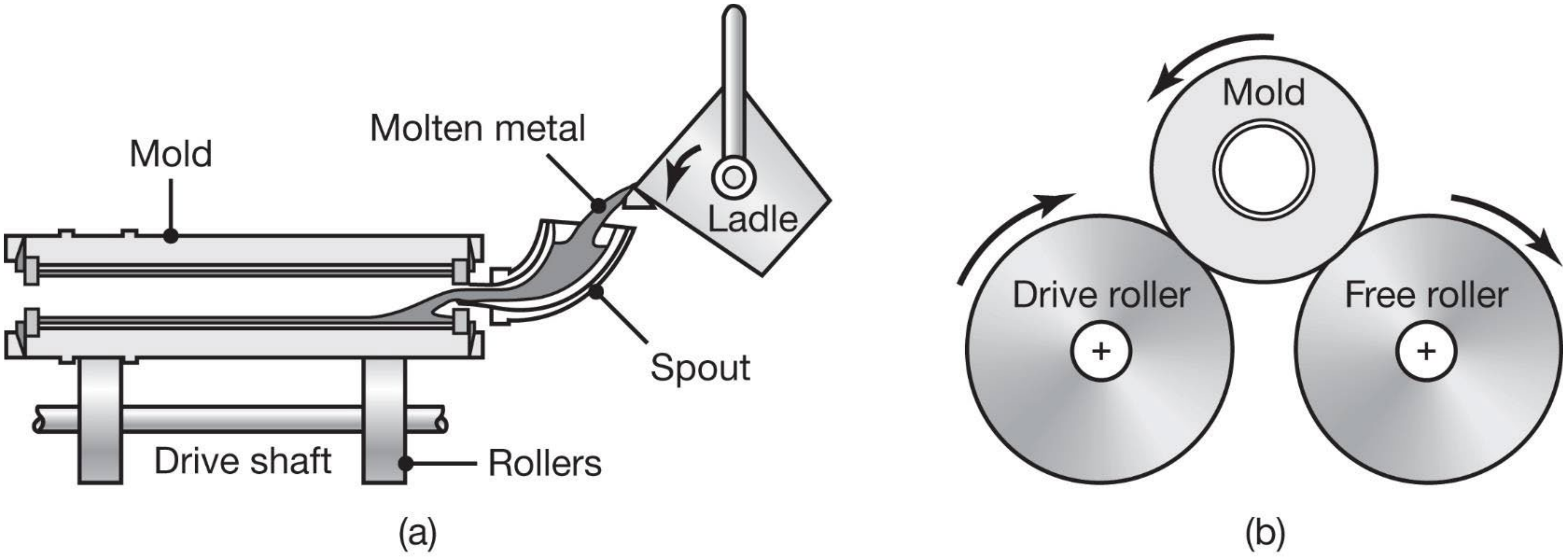
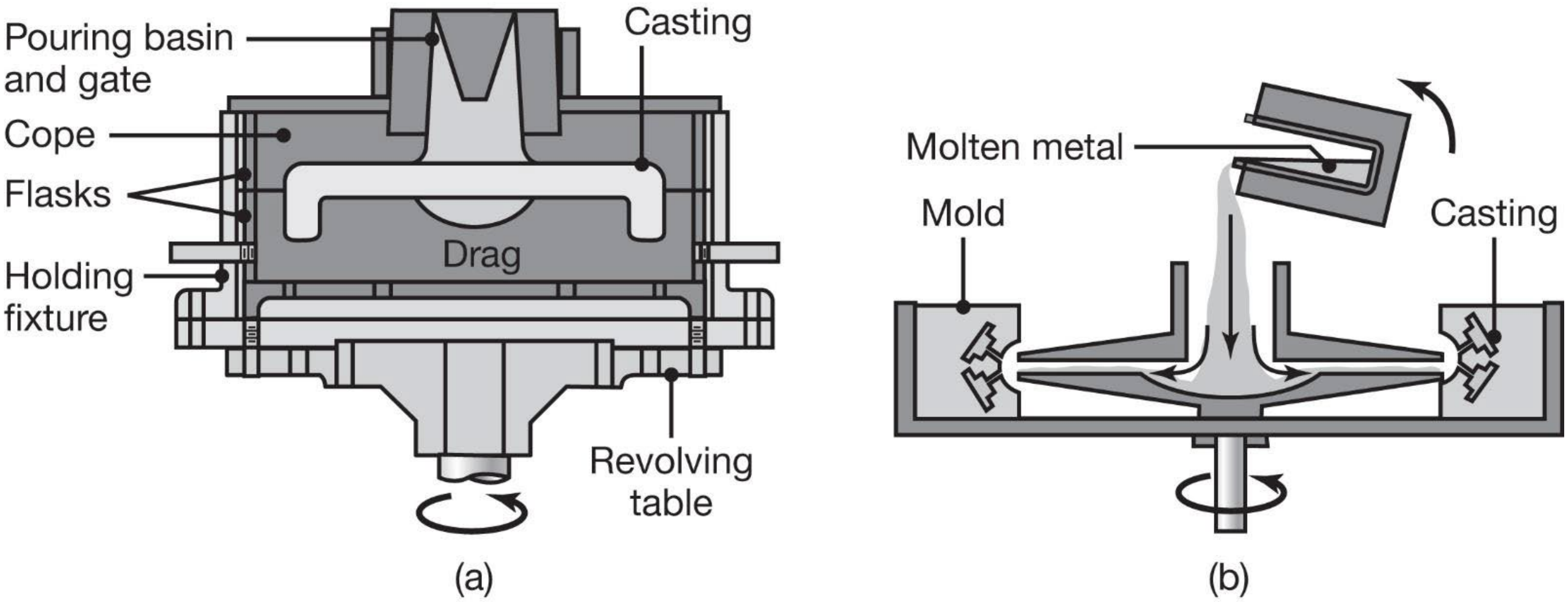


Illustration (MetalTek Int.): https://youtu.be/o4vkUHb91H0

(source: S. Kalpakjian, Manufacturing, Pearson Ed.)

Semi-centrifugal process



(source: S. Kalpakjian, Manufacturing, Pearson Ed.)

Die casting

- Use of a metal die
- Injection of metal into the die

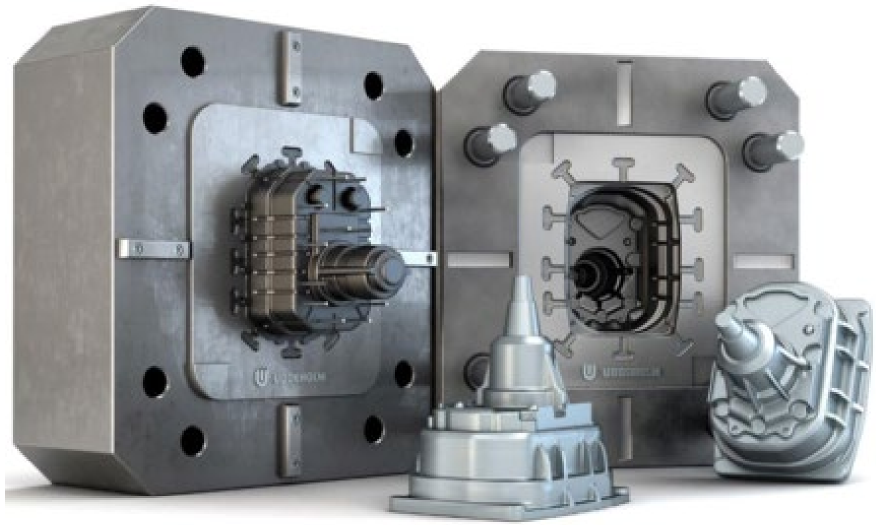
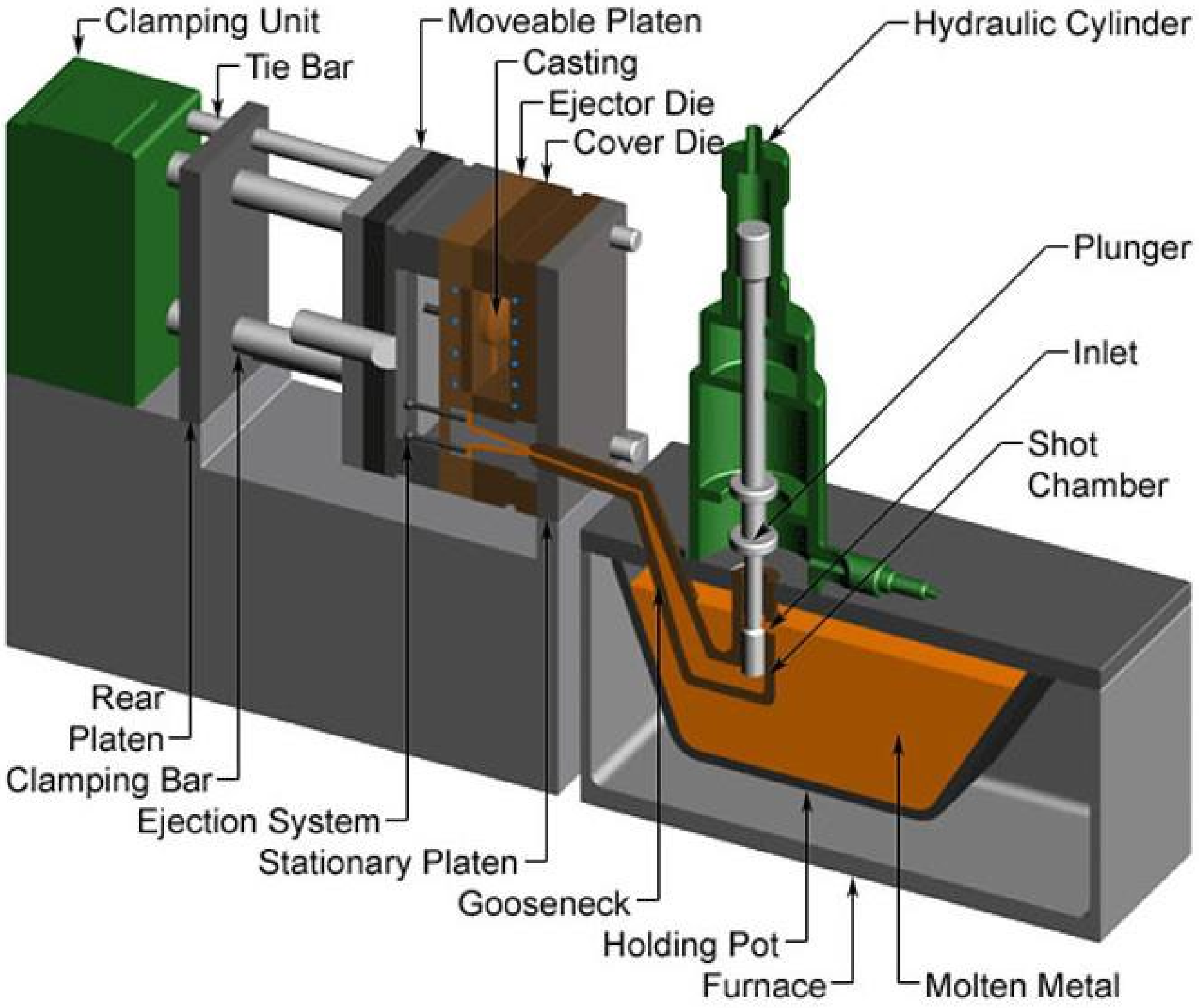
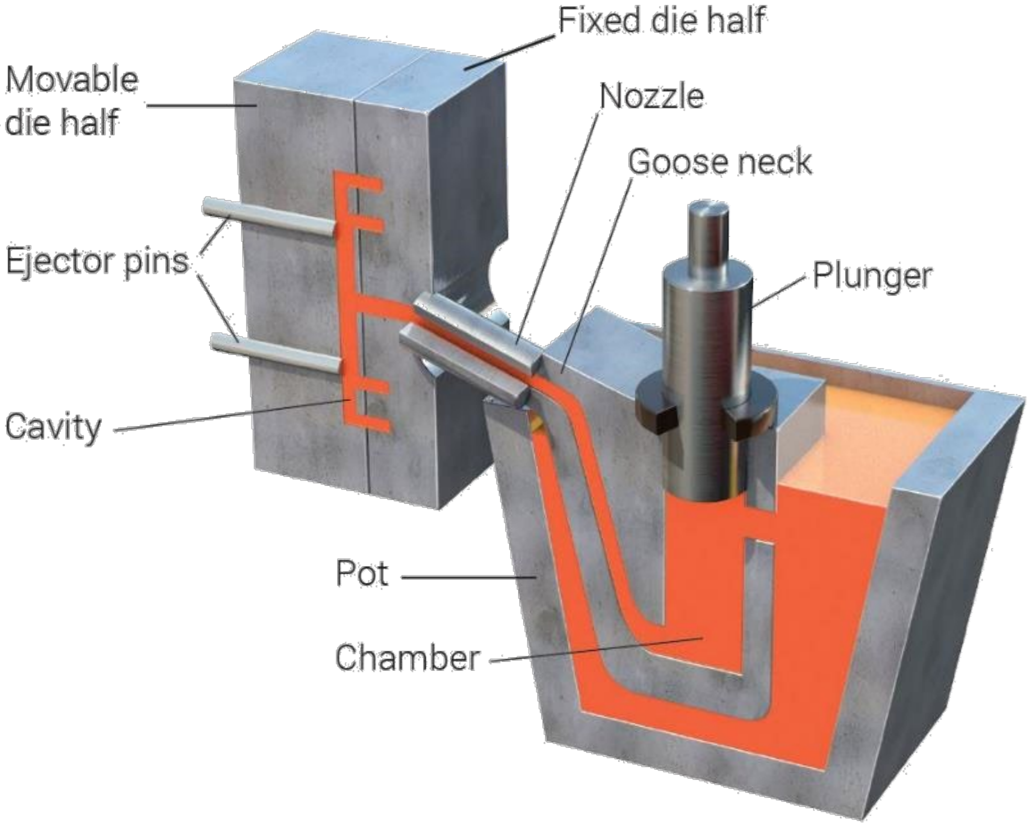


Photo credit: Mannat Engineering Works

Die casting





Source:www.engineeringclicks.com

- Various principles for dispensing the hot metal

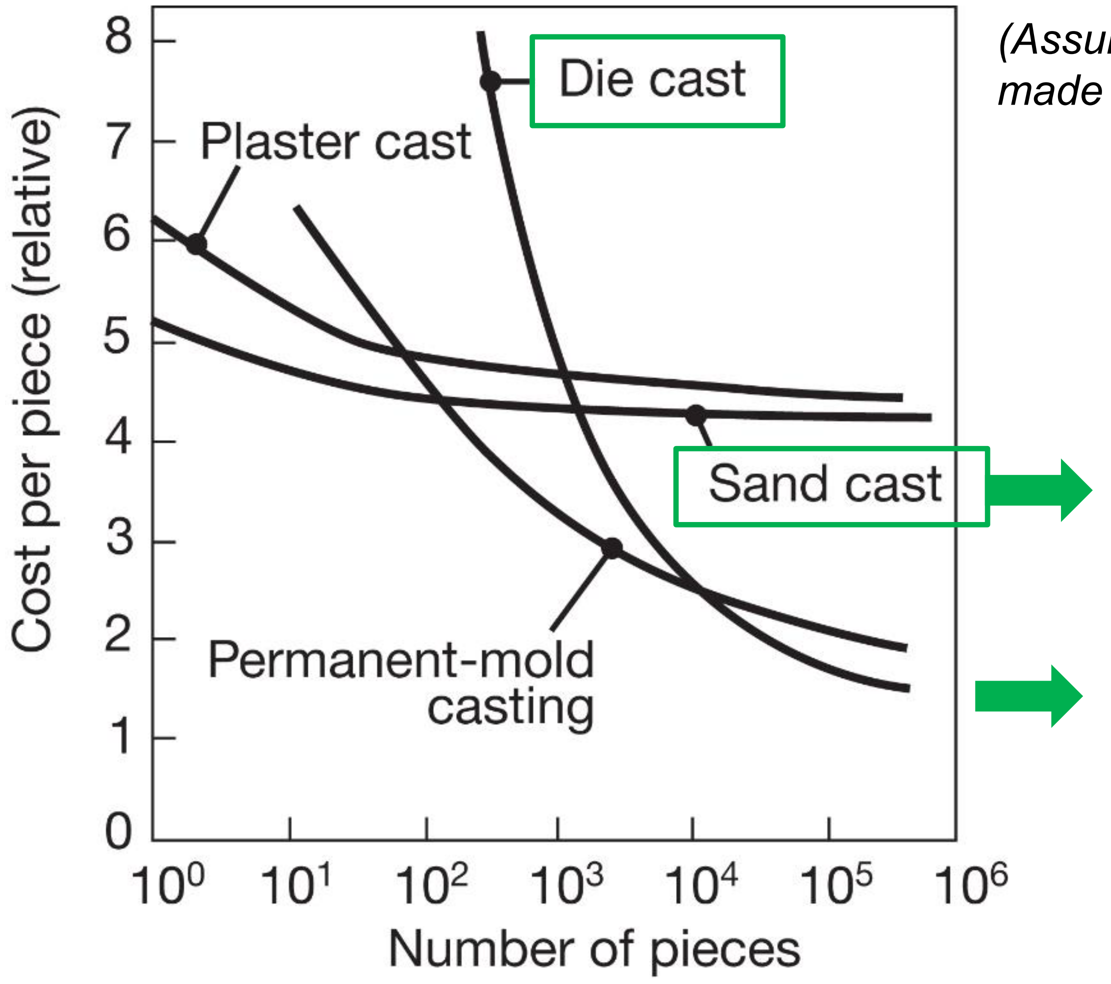
(illustration: A&B Die Casting)

Comparison

Process	Advantages	Limitations
Sand	Almost any metal can be cast; no limit to size, shape or weight; low tooling cost	Some finishing required; somewhat coarse finish; wide tolerances
Shell mold	Good dimensional accuracy and surface finish; high production rate	Part size limited; expensive patterns and equipment required
Expendable pattern	Most metals cast with no limit to size; complex shapes	Patterns have low strength and can be costly for low quantities
Plaster mold	Intricate shapes; good dimensional accuracy and finish; low porosity	Limited to nonferrous metals; limited size and volume of production; mold making time relatively long
Ceramic mold	Intricate shapes; close tolerance parts; good surface finish	Limited size
Investment	Intricate shapes; excellent surface finish and accuracy; almost any metal cast	Part size limited; expensive patterns, molds, and labor
Permanent mold	Good surface finish and dimensional accuracy; low porosity; high production rate	High mold cost; limited shape and intricacy; not suitable for high-melting-point metals
Die	Excellent dimensional accuracy and surface finish; high production rate	Die cost is high; part size limited; usually limited to nonferrous metals; long lead time
Centrifugal	Large cylindrical parts with good quality; high production rate	Equipment is expensive; part shape limited

(source: S. Kalpakjian, Manufacturing, Pearson Ed.)

Cost comparison between processes



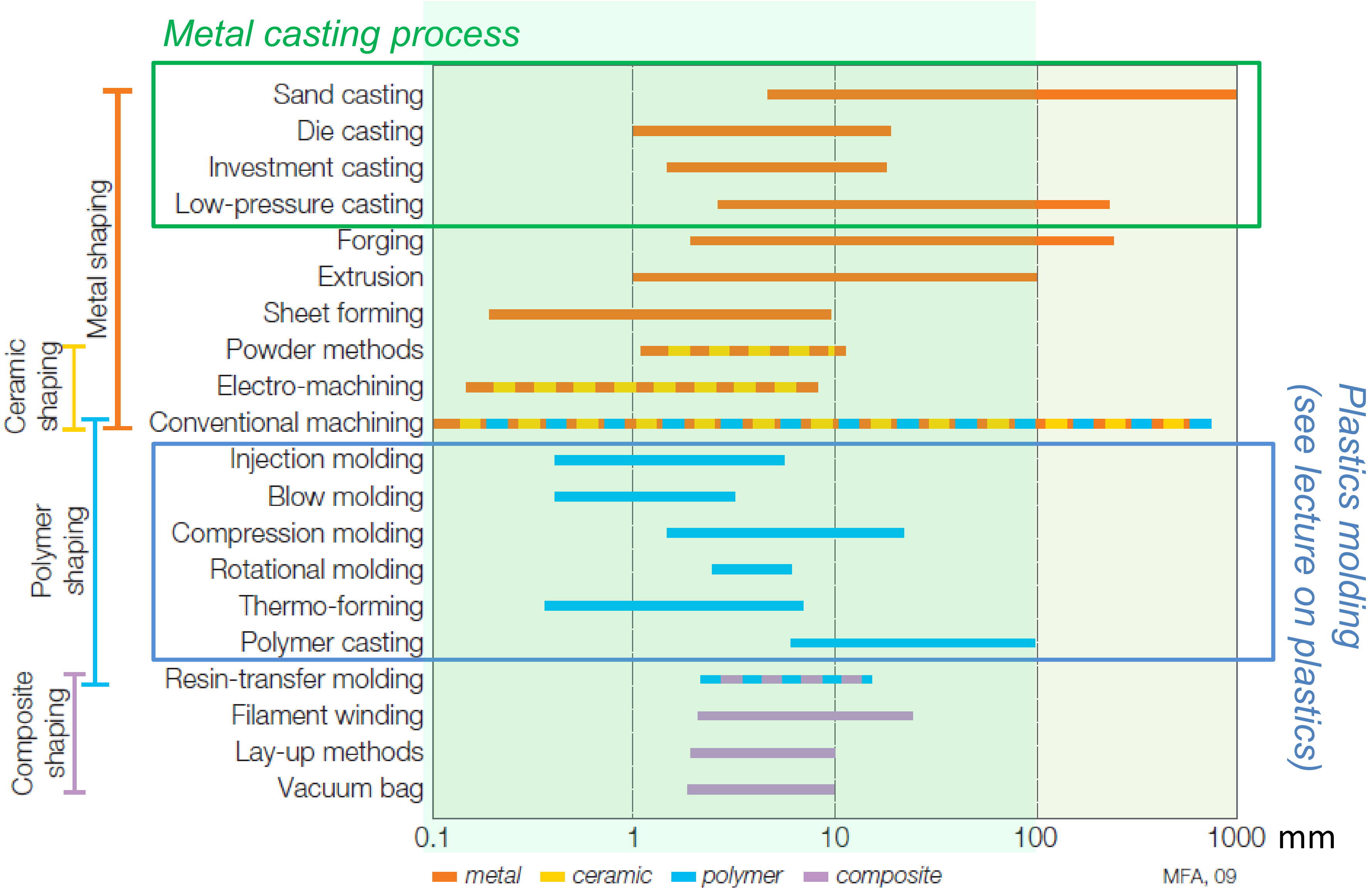
(Assuming the same part can be made using all these processes)

Low-tooling cost, limited effect of the number of parts on the cost

High-tool cost (typ. mold price is >20kCHF), only economically viable if the number of parts is sufficiently high

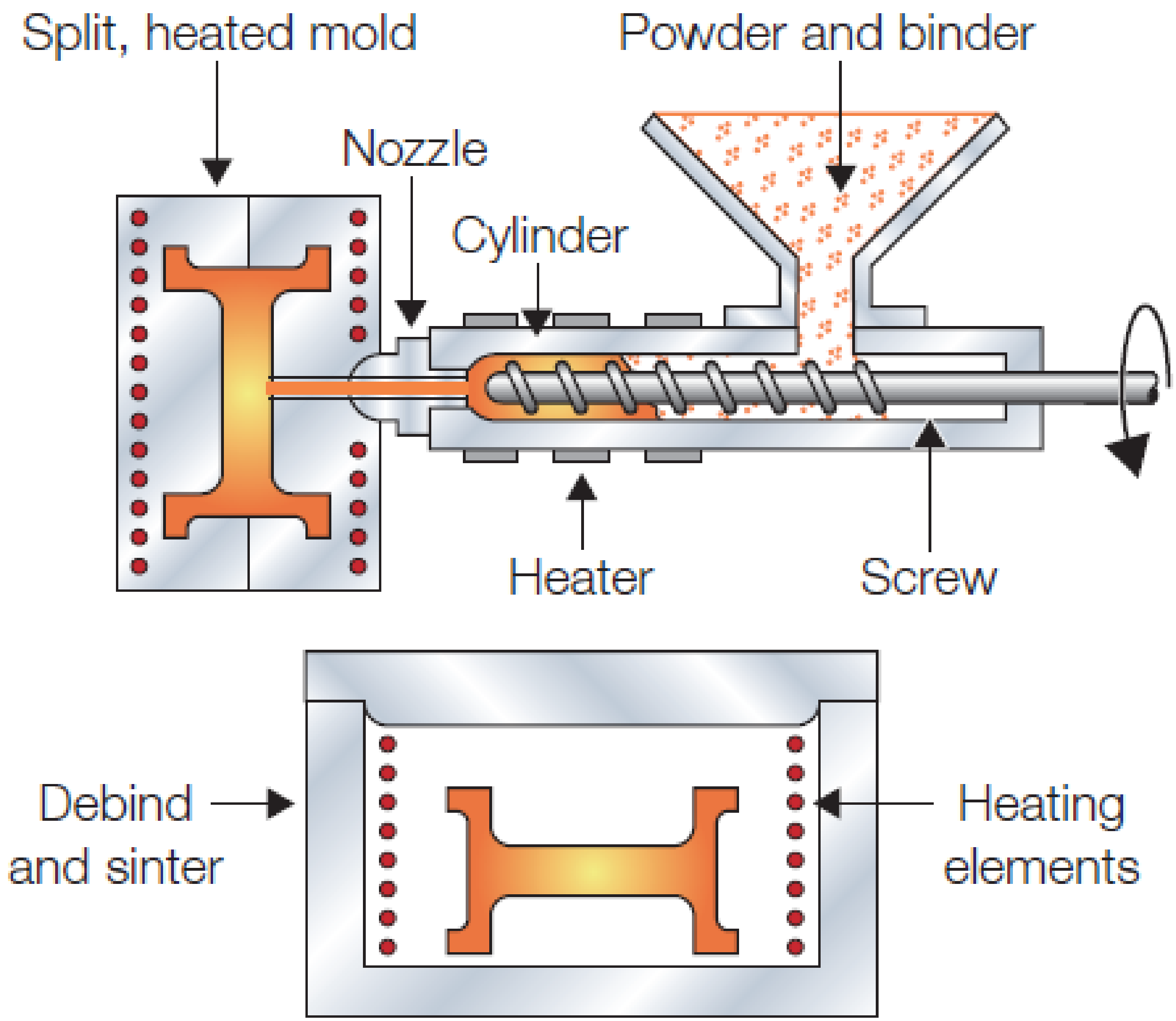
(source: North American Die Casting Association.)

Size limit between manufacturing processes



(Adapted from M. Ashby)

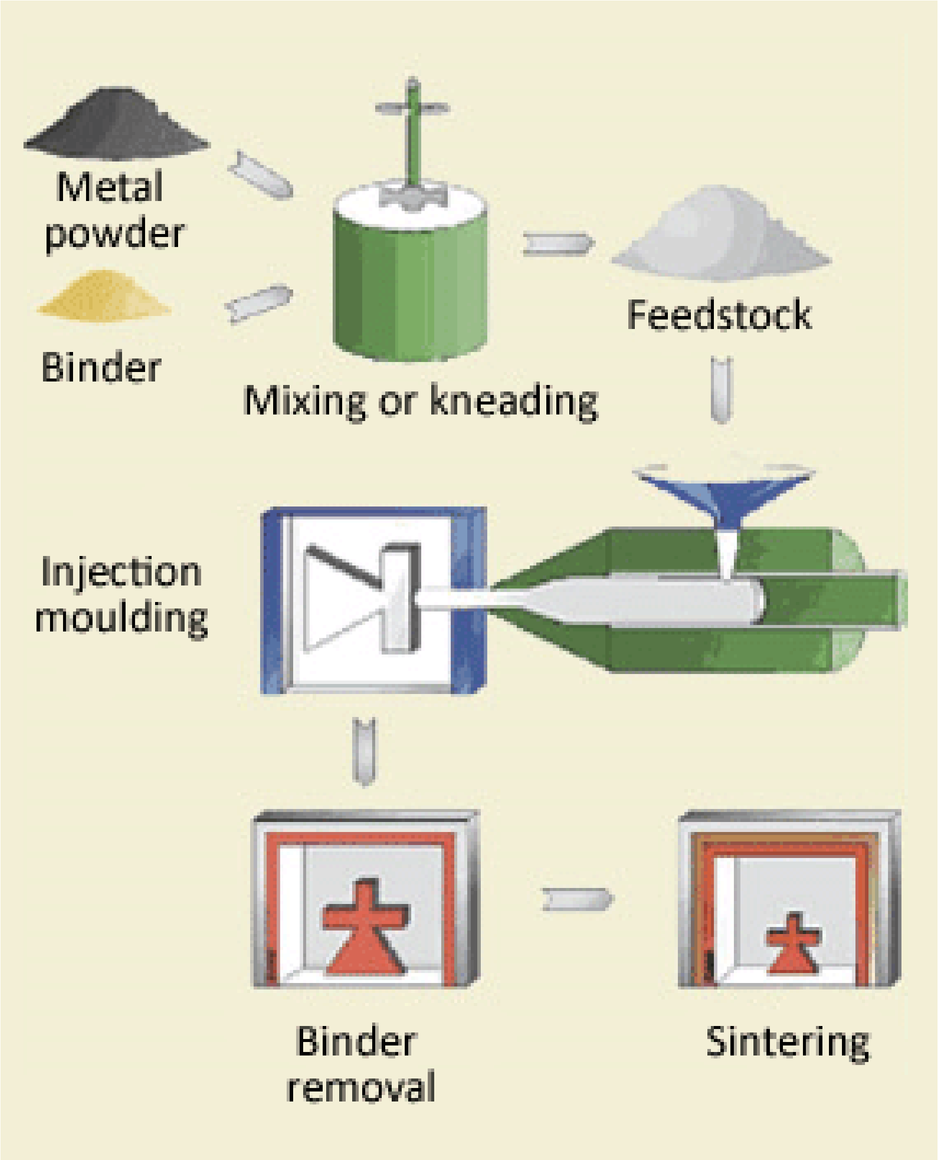
Metal injection Molding



(source Ashby)

Working principle explained:
https://youtu.be/MmLYj3GZsx8

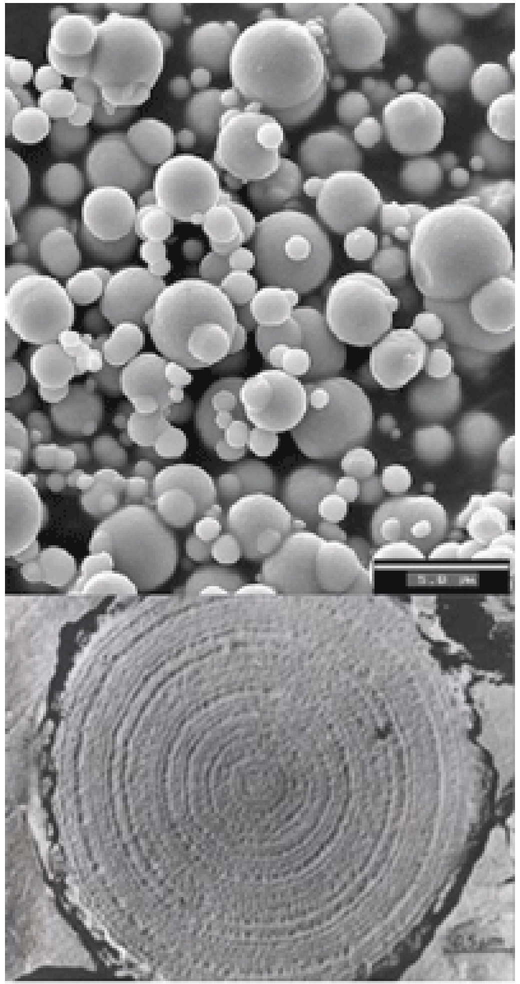
Metal injection molding



- **Step 1:** Preparing the feed stock
  - Metal powder
  - Thermoplastic binder
- **Step 2:** Injection molding
- **Step 3:** Binder removal
  - Catalytic debinding /Nitric and Oxalic acids @ 120 deg C or Solvent debinding
  - Network of pores
- **Step 4:** Sintering
  - Typ. shrinkage: 15 to 20 %
- **Step 5:** Optional post-processing steps (ex. Hot Isostatic Pressing)

Basic principle of a metal injection molding process (Source: Pim-International) - Illustrative video: https://youtu.be/MmLYj3GZsx8

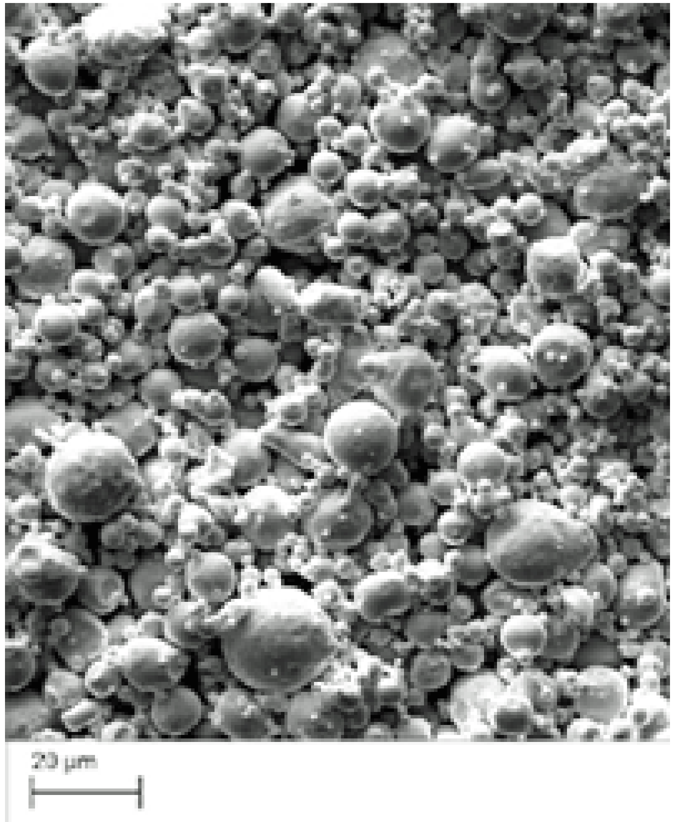
Powders production



< Carbonyl iron and nickel powders

Powders are mixed with elemental or master alloy powders to achieve the desired alloy composition.

Carbonyl iron powder (SEM, top, with scale showing 5µm) and cross-section of a particle (Image BASF, Germany)



Water and gas atomized powders >

Used essentially for alloys. (Image Sandvik Osprey, UK)

Binders functions

- To be able to incorporate a **high volume of fine metal** or **ceramic powders**, typically **60%** by volume
- Form a coherent mass that can be plasticized, and **injection molded at elevated temperature**
- Allow removal of the main binder constituent in a reasonably short time and environmentally friendly process
- Still provide enough strength after debinding by means of the 'backbone binder'
- Be supplied in **a regular granular form** that can easily be fed into an injection molding machine

Illustration of the shrinkage during debinding

Metal Injection Molded housing cover made from 316L stainless steel (sensor casing).
Before and after sintering. (source PIM International Vol.4 No.1, March 2010)

Examples of part produced by MIM

MIM knee implant parts made from Ti6Al4V
(Maetta Sciences Inc., Canada.)

Post-treatments: bead blasting, electropolishing and anodizing

17-4 PH stainless steel articulation gear manufactured by Parmatech Inc, USA. (Image Courtesy MPIF, USA)

BMW engines, **metal Injection molded rocker arms** produced by Schunk Sintermetalltechnik GmbH , Germany – Alloy: hardenable 50NiCrMo2.2 steel powder alloy

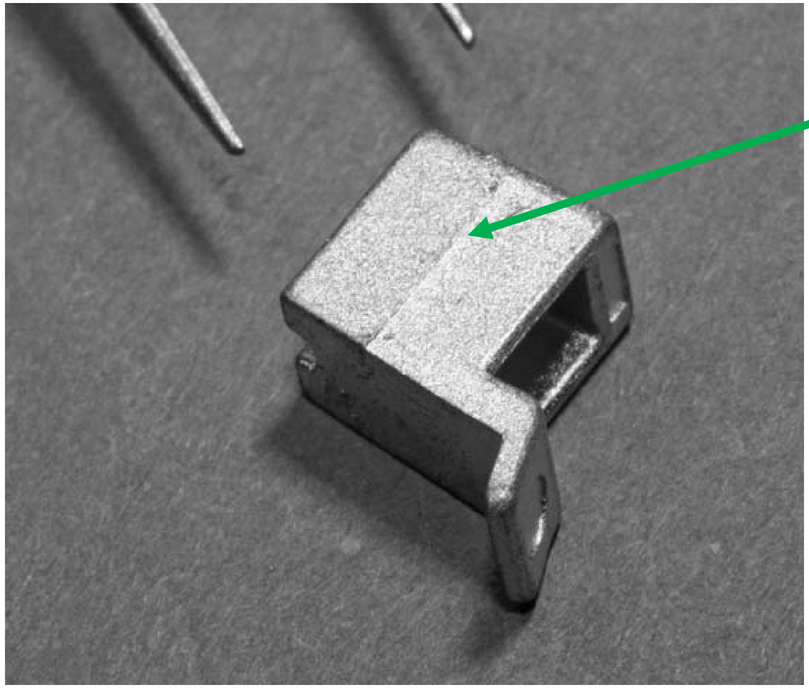
Examples of part produced by MIM

Apple connector. (at peak production: 10 Millions of parts per week !)

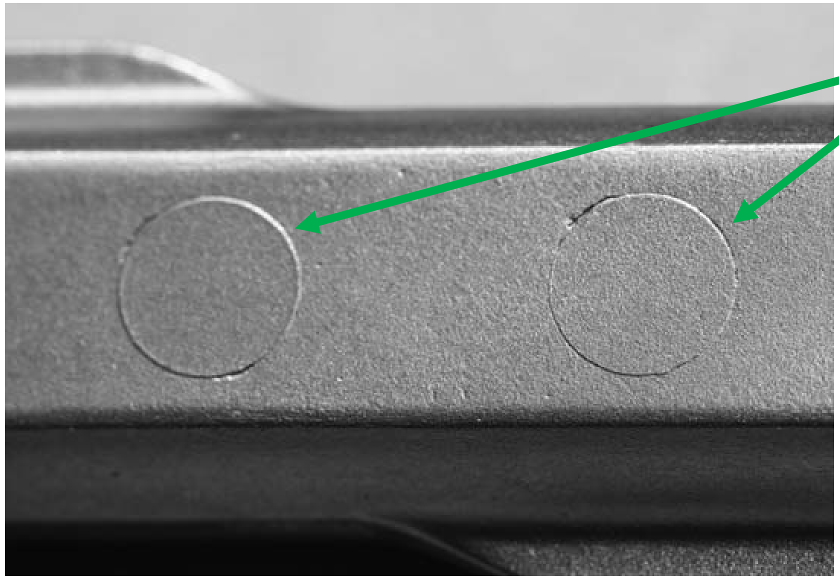
Seat belt component for airplanes (image: MimEcrisa SA, Spain)
m = 90 g / Fe7Ni0.6C steel alloy
UTS (after heat treatment) > 1200 MPa

Swatch Irony (stainless-steel MIM cases).

Illustrations



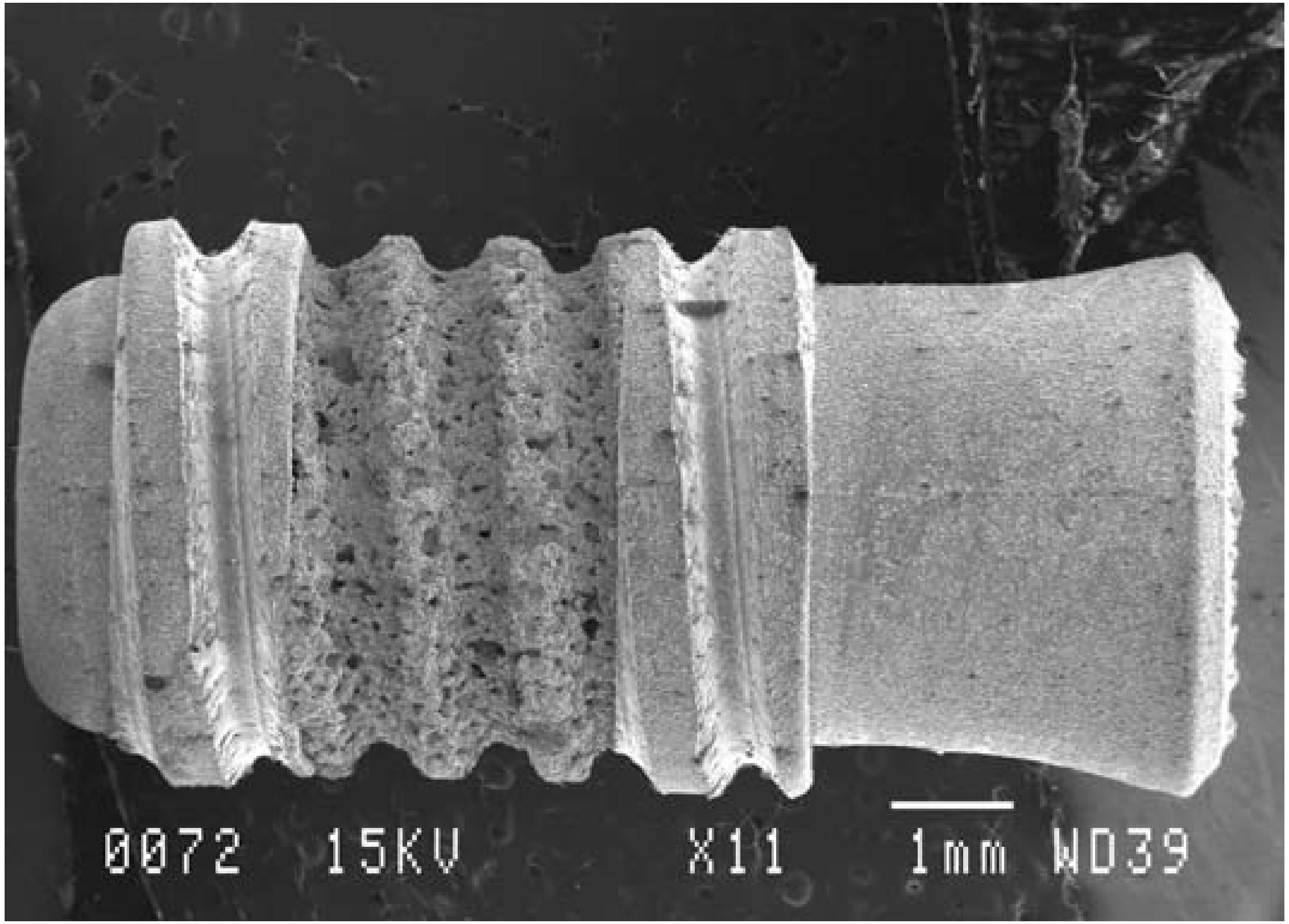
Parting line blemish on a MIM component showing where the two halves of a tool come together.



Typical ejector pin marks shown on a MIM component

Tab gate blemish along parting line on a MIM component.

Examples



Titanium dental implant formed by MIM with an intentional porous region for bone ingrowth (book: Handbook of metal injection molding photograph courtesy of Eric Baril).

Comparison with other processing techniques (indicative)

Metal injection molding | 3D printing | Reference

Attribute	MIM	Powder metallurgy	Casting	Machining
Component size (g)	0.030–300	0.1–10 000	1 +	0.1 +
Wall thickness range (mm)	0.025*–15	2 +	5 +	0.1 +
Percent theoretical density (%)	95–100	85–90	94–99	100
Percent theoretical strength (%)	95–100	75–85	94–97	100
Surface finish (µm)	0.3–1	2	3	0.4–2
Production volume	2000 +	2000 +	500 +	1 +

*Features this small could have distortion.

(source: Handbook of injection molding)

Pros & Cons

- **Simplified** the machining of complex parts (reduced number of operations)
- **Suited for high volume production** (> typ. over 20’000 parts to millions of parts)
- Relative **high raw materials cost** => acceptable for parts where the material cost is not the main manufacturing cost (smaller size parts)
- **Denser** than part produced by powder metallurgy (but less than conventional machining)
- Surface finish comparable to conventional machining
- Part volume shrinkage to consider (15 to 20%)
- Well adapted to small parts

MIM specs (indicative)

Attribute	Minimum	Typical	Maximum
Component mass (g)	0.030	10–15	300
Max. dimension (mm)	2 (0.08 in)	25 (1 in)	150 (6 in)
Min. wall thickness (mm)	0.025 (0.001 in)*	5 (0.2 in)	15 (0.6 in)
Tolerance (%)	0.2%	0.5%	1%
Density	93%	98%	100%
Production quantity	1000	100 000	100 000 000

*Features this small could have distortion.

(source: Handbook of injection molding)

Available materials (PIM)

Table 2.3 Overview of MIM materials, applications, and features

Material family	Applications	Specific alloys	Specific feature
Stainless steel	Medical, electronic, hardware, sporting goods, aerospace, consumer products	17-4PH	Strength, heat treatable
		316L	Corrosion resistance, ductility, non-magnetic
		420, 440C	Hardness, wear resistance, heat treatable
		310	Corrosion and heat resistance
Low-alloy steel	Hardware, bearings, races, consumer goods, machine parts	1000 series	Case hardenable
		4000 series	General purpose
		52100	High wear resistance
Tool steel	Wood and metal cutting tools	M2/M4	61–66 HRC
		T15	63–68 HRC
		M42	65–70 HRC
		S7	55–60 HRC
Titanium	Medical, aerospace, consumer products	Ti	Light weight
		Ti–6Al–4V	Light weight, high strength
Copper	Electronic, thermal management	Cu	High thermal and electrical conductivity
		W–Cu, Mo–Cu	High thermal conductivity, low thermal expansion
Magnetic	Electronic, solenoids, armatures, relays	Fe–3%Si	Low core losses and high electrical resistivity
		Fe–50%Ni	High permeability and low coercive field
		Fe–50%Co	Highest magnetic saturation
Tungsten	Military, electronic, sporting goods	W	Density
		W heavy alloy	Density and toughness
Hardmetals	Cutting and wear applications	WC–5Co	Higher hardness
		WC–10Co	Higher toughness
Ceramics	Wear applications, nozzles, ferules	Alumina	General purpose
		Zirconia	High wear resistance

Part II – Analysis of casting

Physics of casting...

- **Fluid mechanics** (Mold filling)
- **Heat transfer** (solidification)
- **Thermodynamics** (material phase, grain nucleation, growth)
- **Material behavior** (structural properties)

Key physics parameters in a casting process

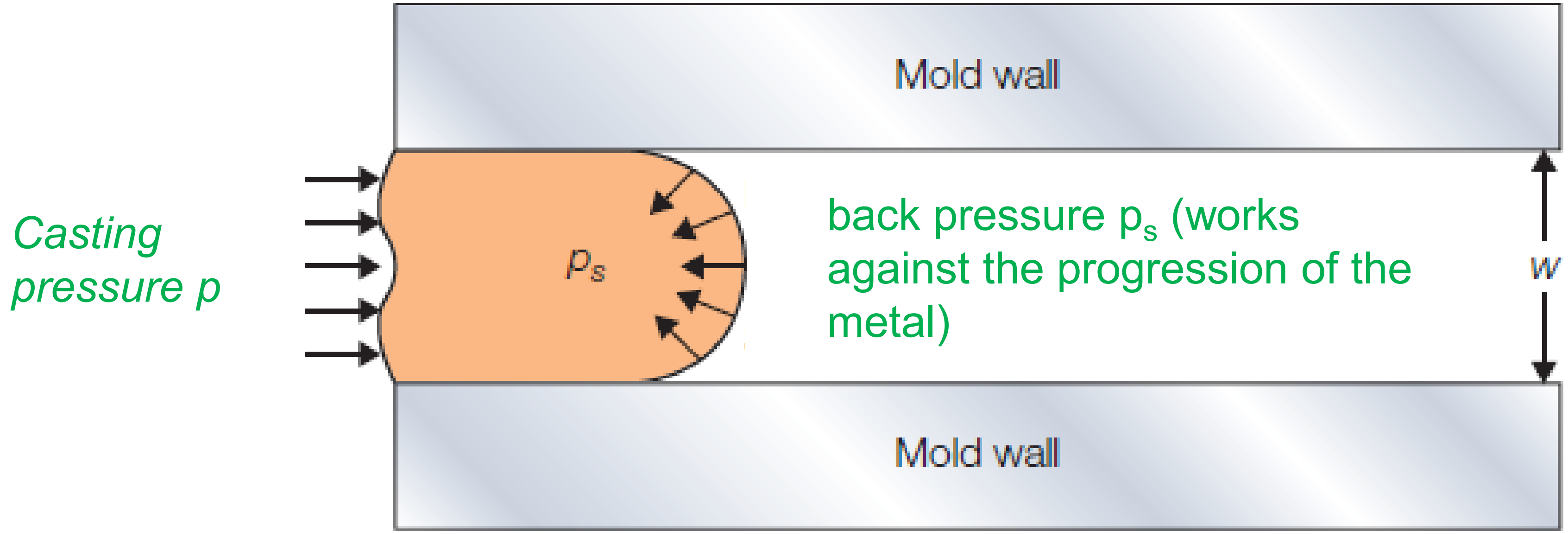
- Mold temperature
- Hot metal temperature
- Flow rate
- Mold volume distribution

Affects →

- *Metal solidification rates*
- *Mold filling*
- *Materials microstructures*

Limit of casting

- Dependence on **flow pressure** of metal through the channels



$$p_s \propto \frac{\gamma}{r}$$

Surface tension of the hot metal (N/m)

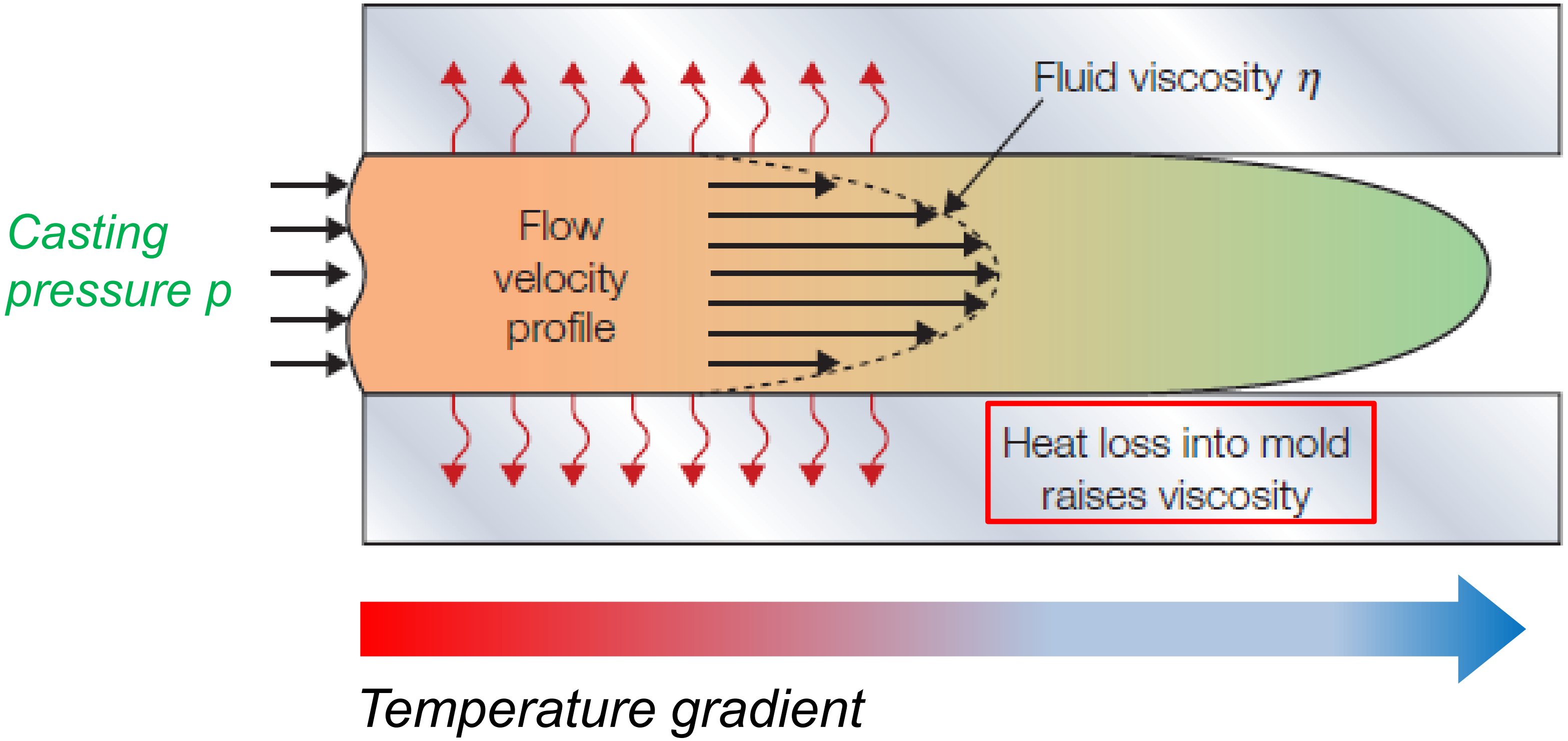
Radius of the meniscus (= w/2)

Infiltration if:

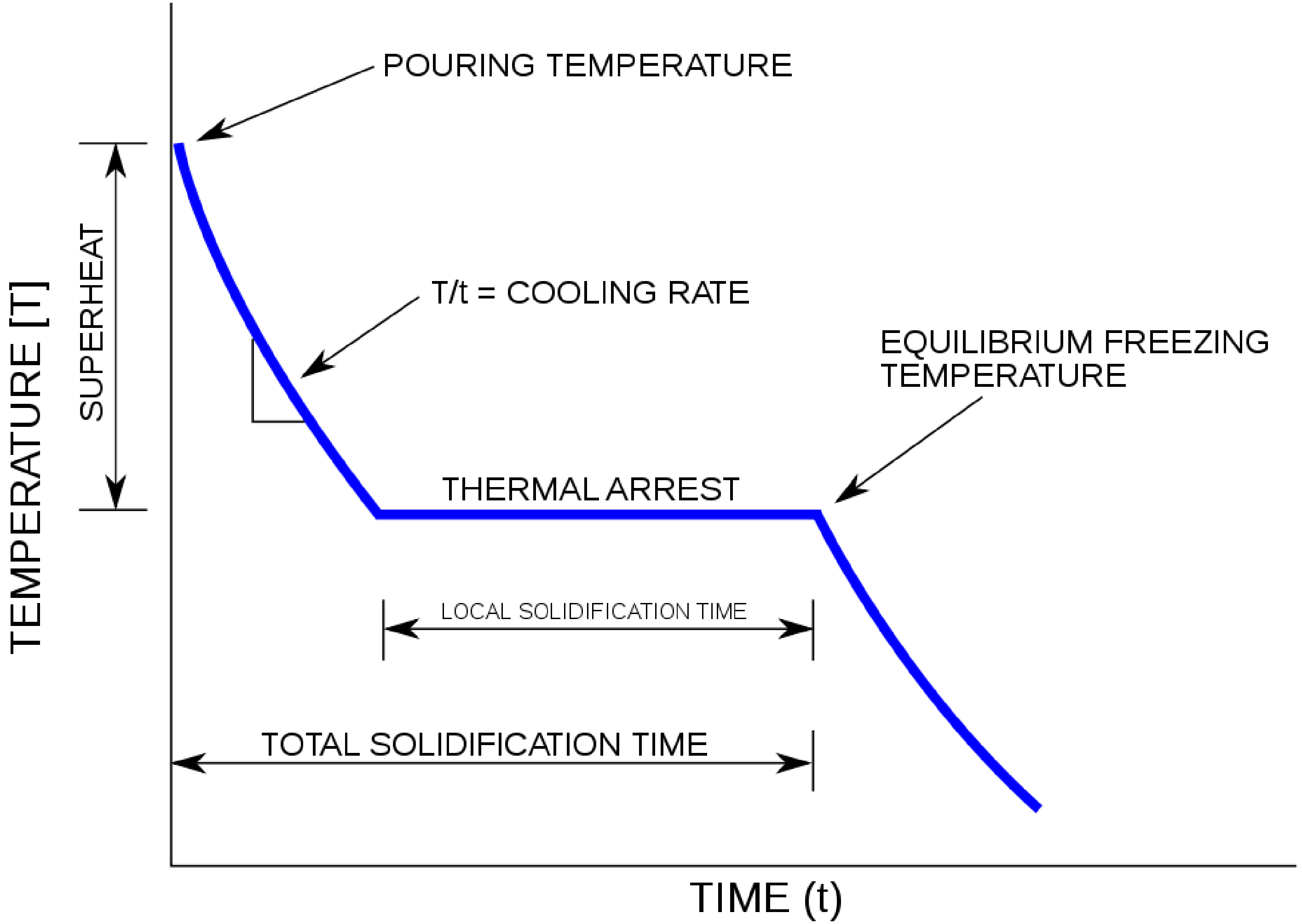
$$p > p_s$$

Limit of casting

- Dependence of the **solidification rate**

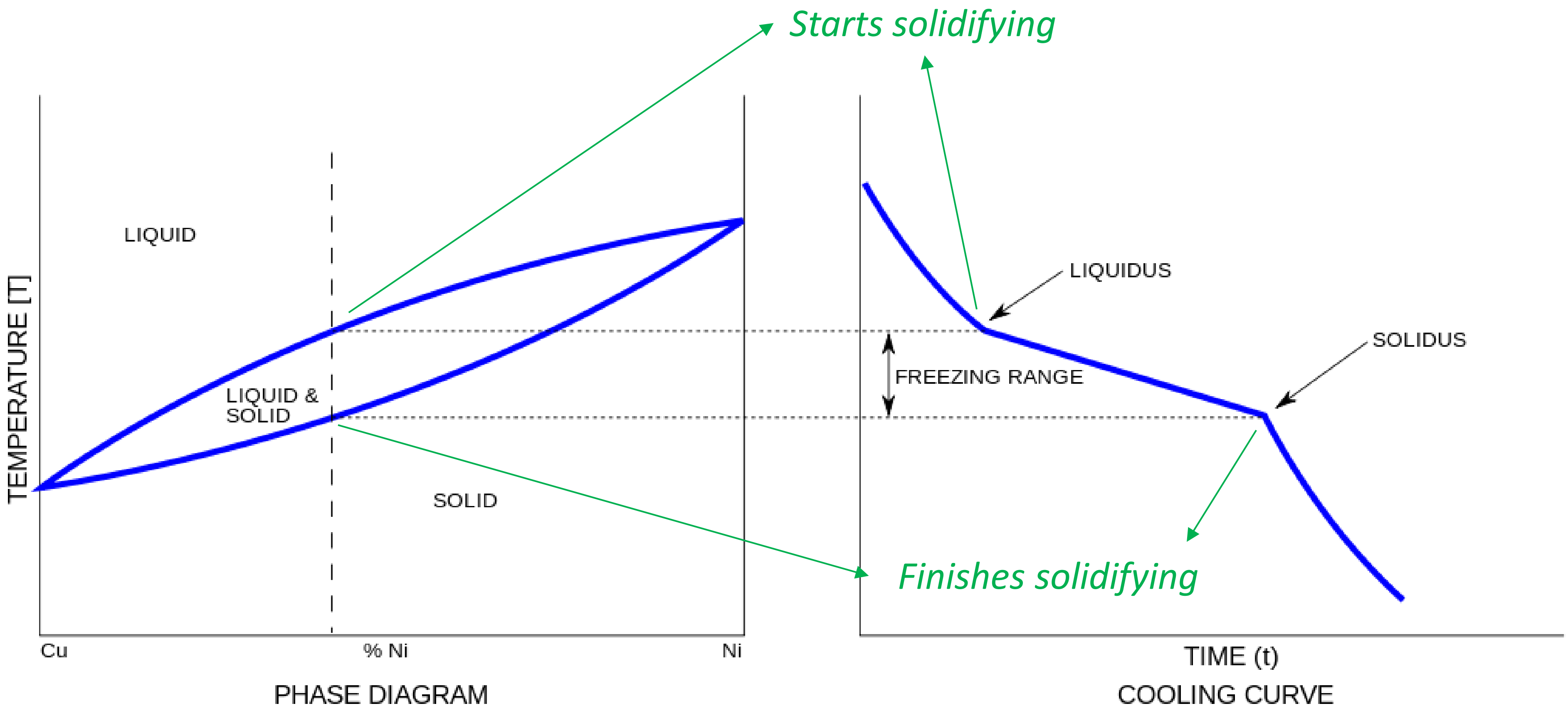


Solidification of a pure metal

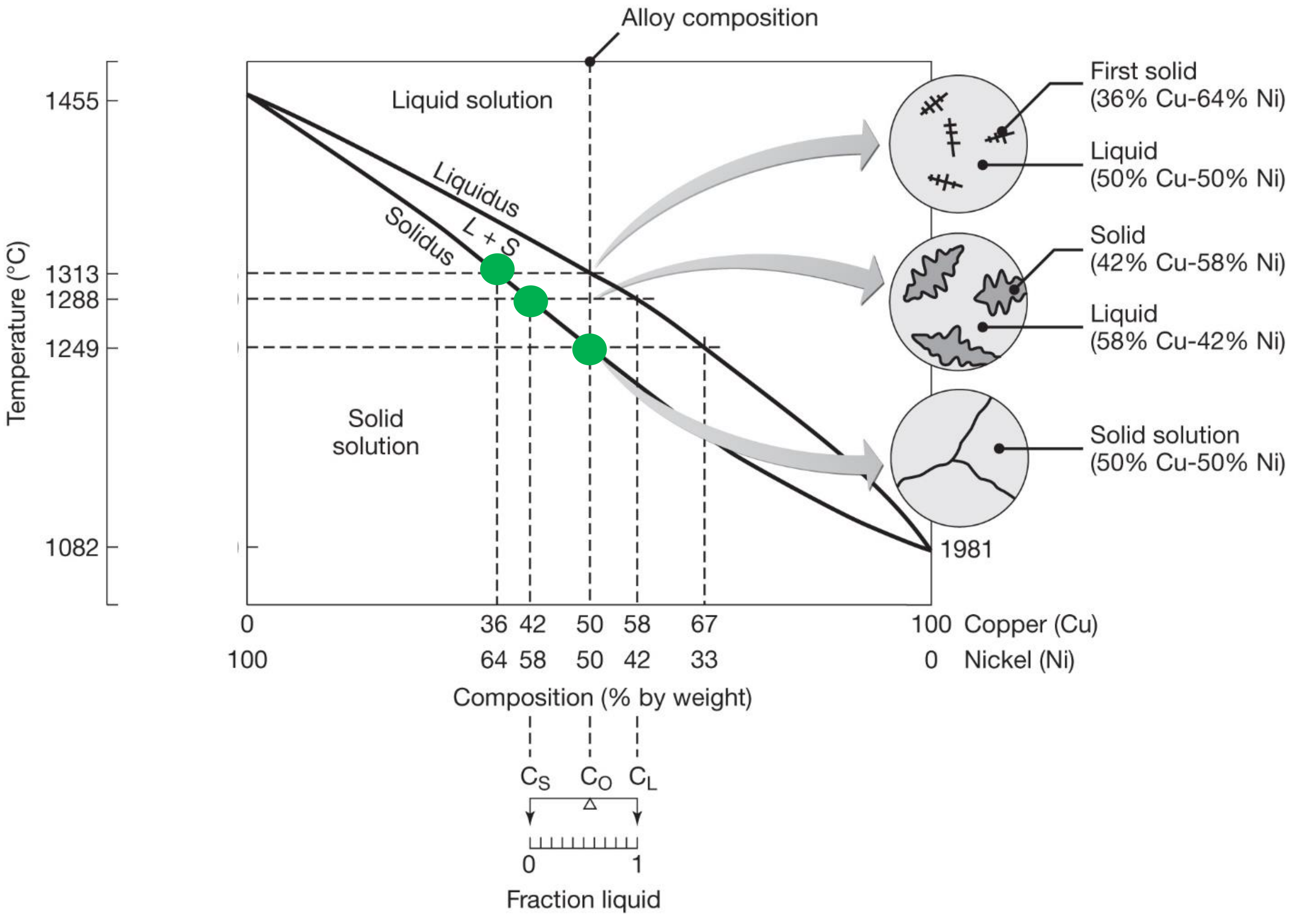


Adapted from Degarmo, E. Paul; Black, J T.; Kohser, Ronald A. (2003), Materials and Processes in Manufacturing (9th ed.), Wiley, ISBN 0-471-65653-4.

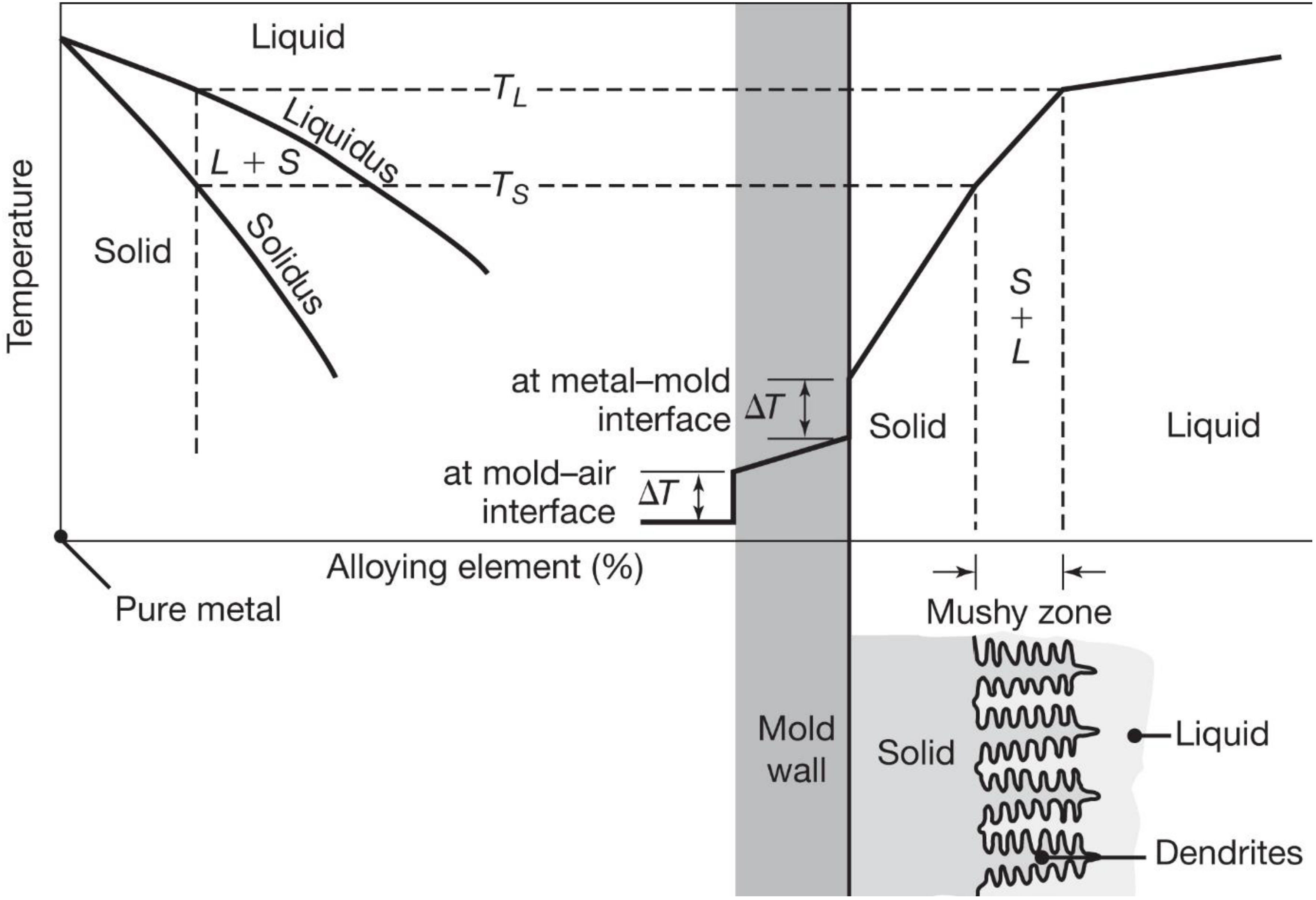
Solidification of an alloy (ex. Cu/Ni)



Adapted from a diagram from Degarmo, E. Paul; Black, J T.; Kohser, Ronald A. (2003), Materials and Processes in Manufacturing (9th ed.), Wiley, [ISBN 0-471-65653-4](#).



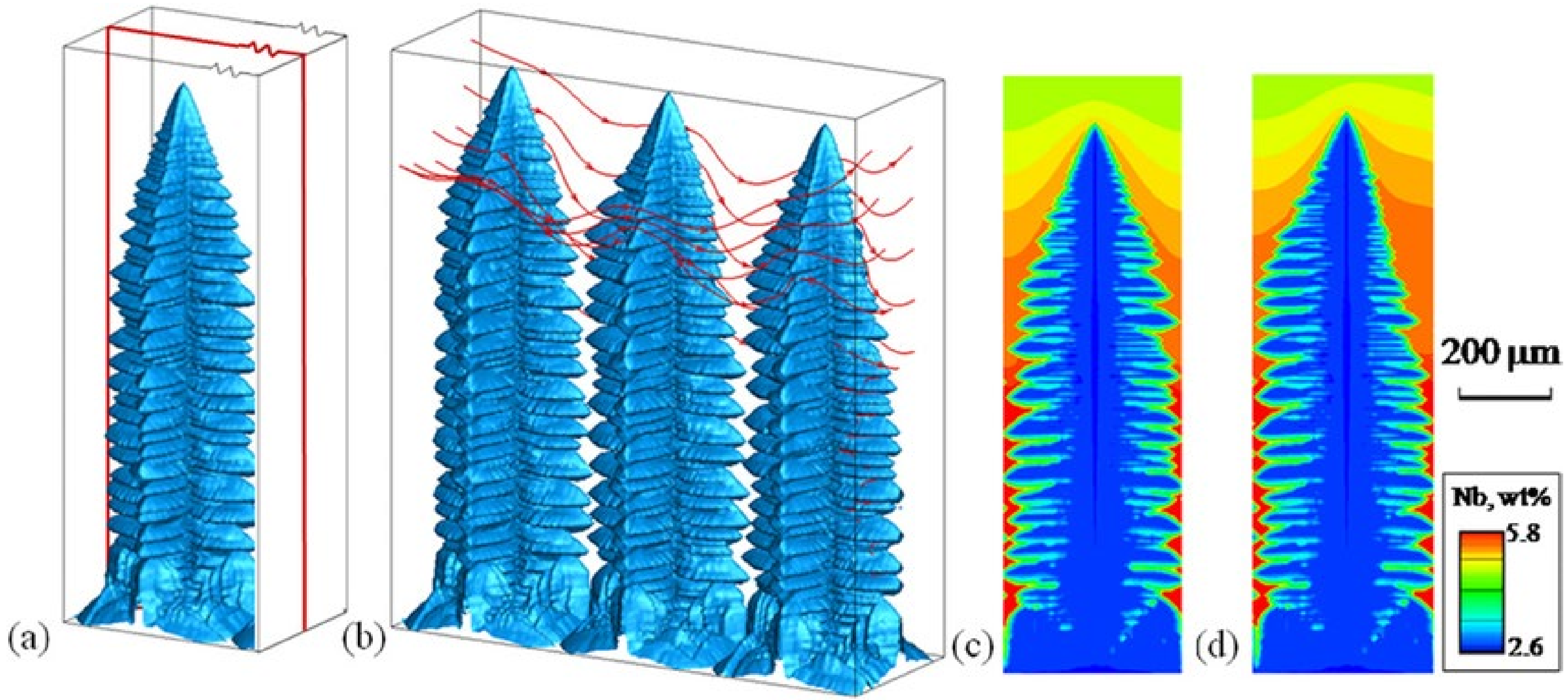
(source: S. Kalpakjian, Manufacturing, Pearson Ed.)



(source: S. Kalpakjian, Manufacturing, Pearson Ed.)

Solidification (Alloys): Dendrites

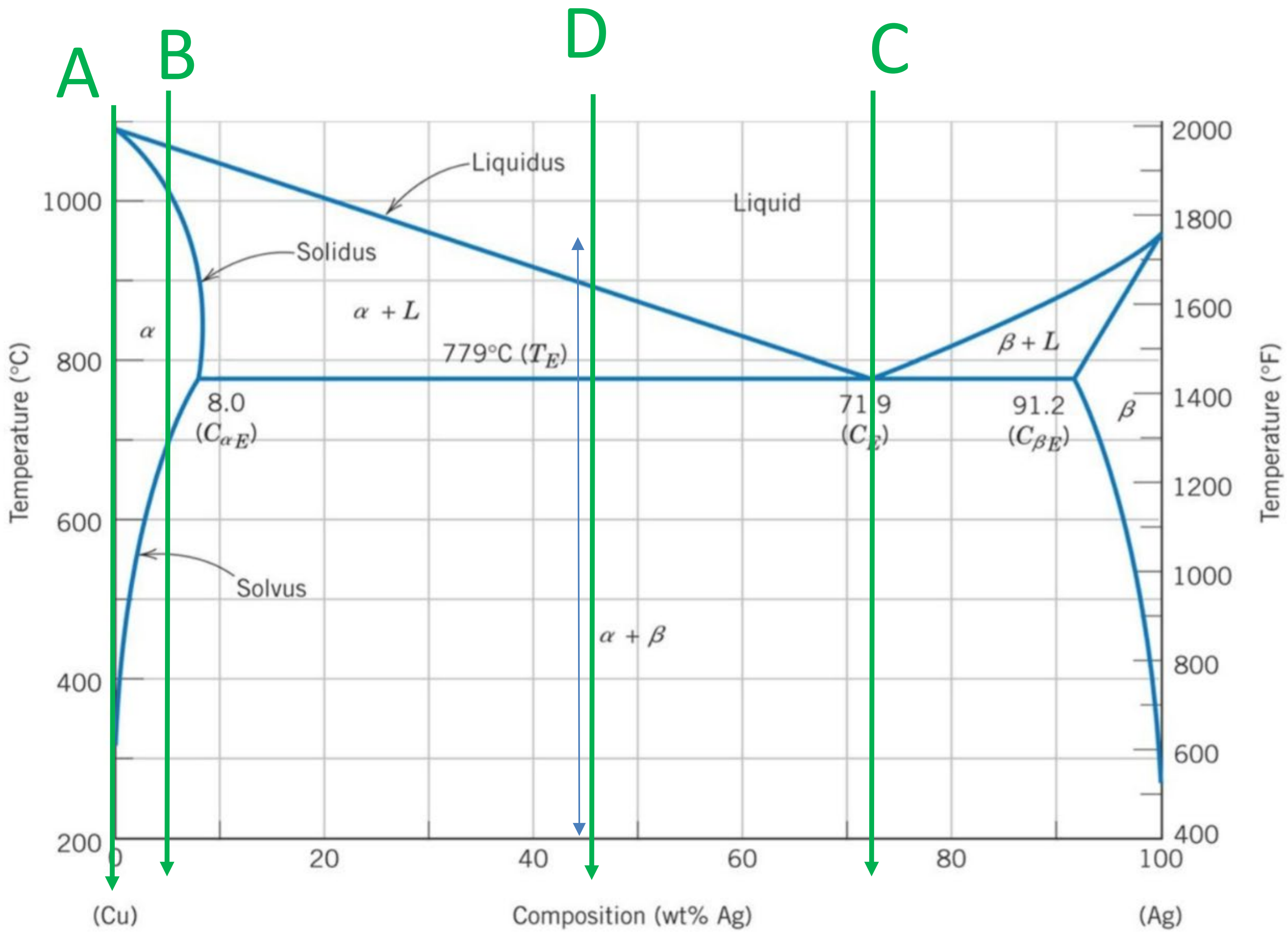
Snowflake



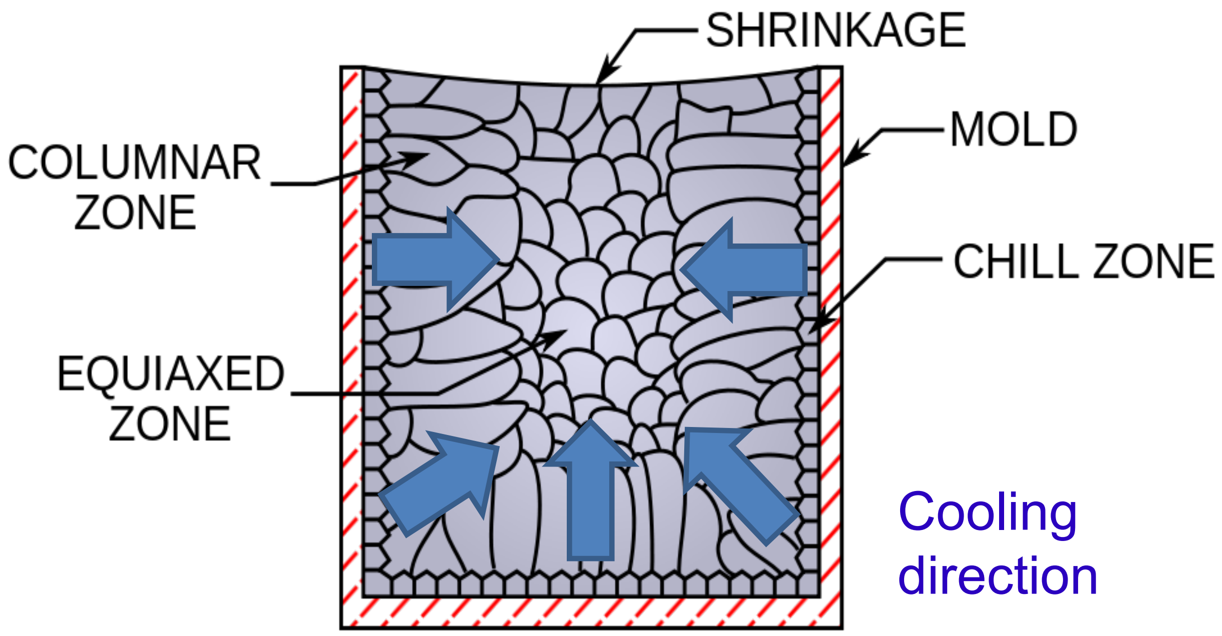
Lang Yuan and Peter D Lee, Dendritic solidification under natural and forced convection in binary alloys: 2D versus 3D simulation, Modelling Simul. Mater. Sci. Eng. ***18*** *(2010) 055008 (13pp)*

If you are curious about dendrites: (Seminar from P. Voorhees, Northwestern Univ.) https://youtu.be/W-yHaZqRrBU

Exercise (homework): describe the material structure evolution for A, B, C, D (Cooling from the liquid phase to the solid ones)



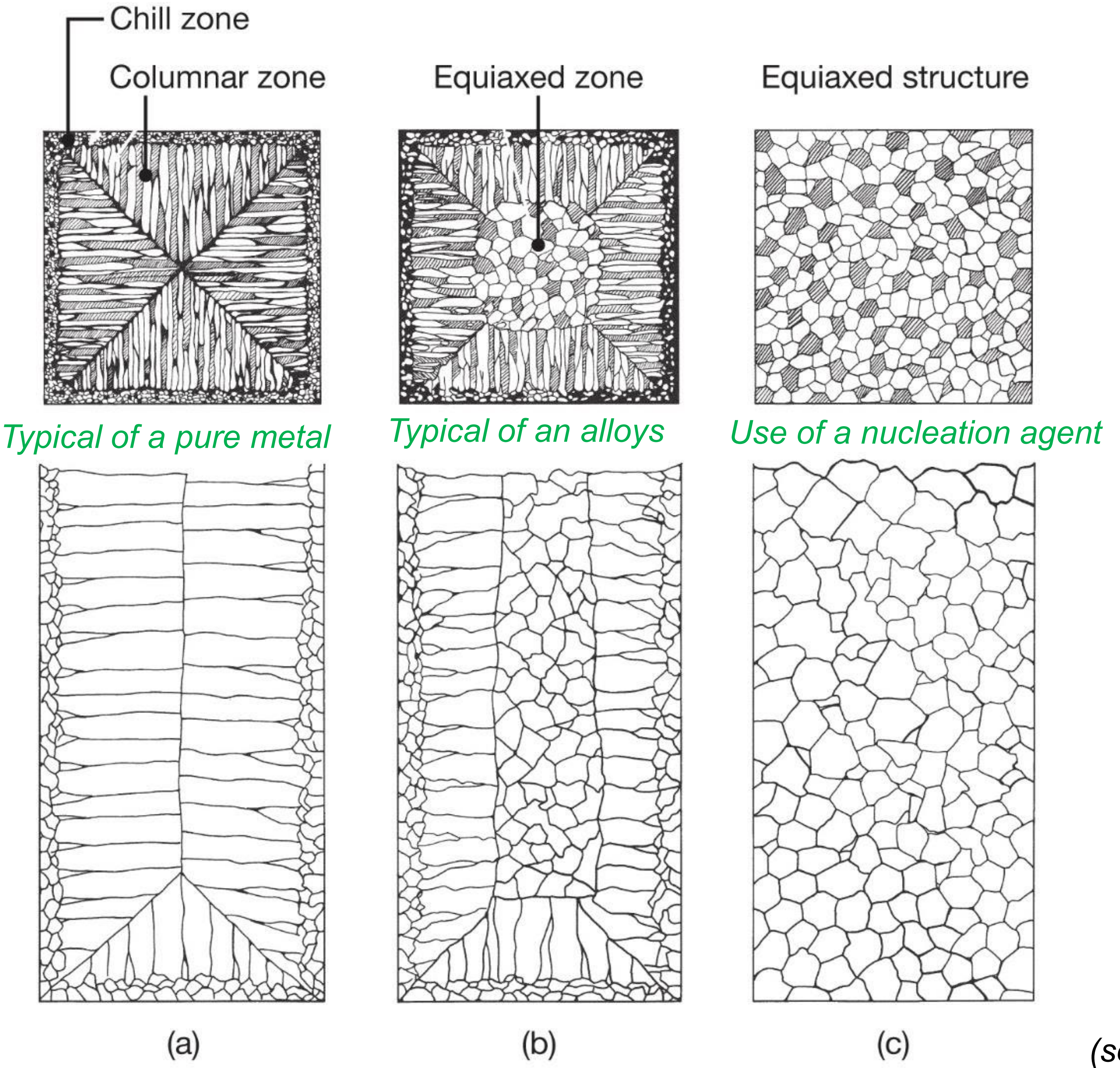
Typical microstructure of a cast ingot



[Adapted from: C. Dang Ngoc Chan (Wiki)]

Image: H. K. D. H. Bhadeshia, Cambridge Univ.

Example of solidified microstructures

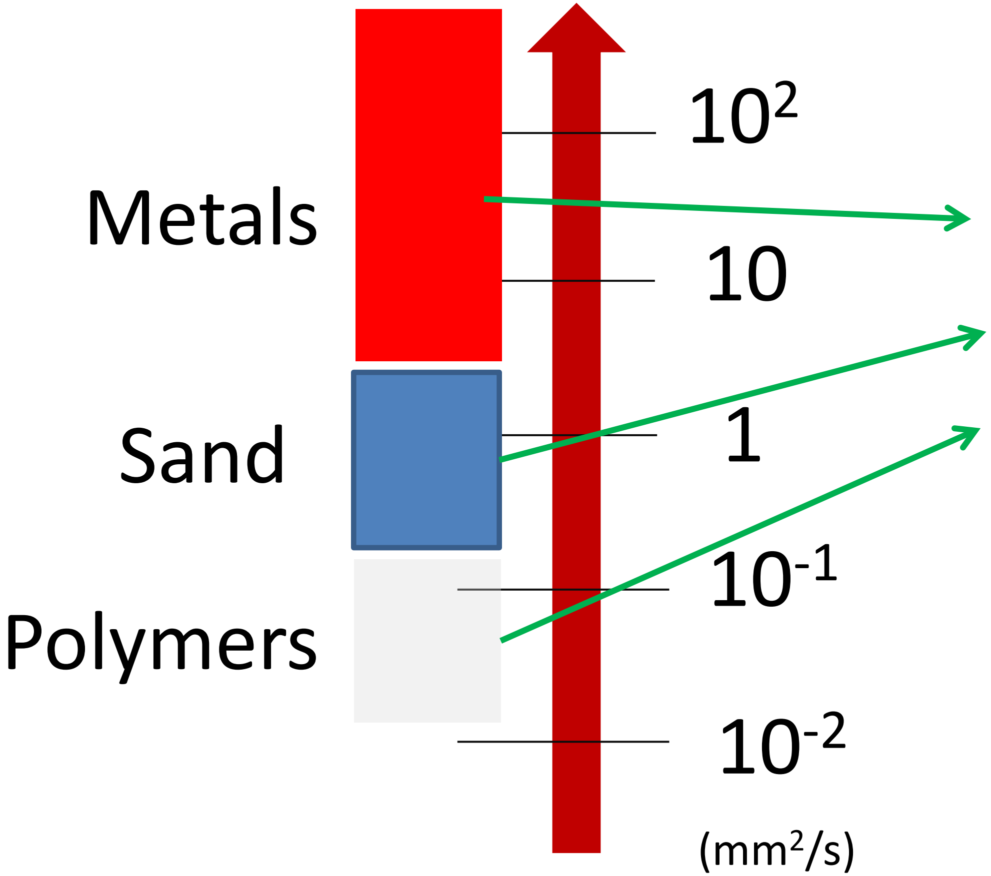


(source: S. Kalpakjian, Manufacturing, Pearson Ed.)

Thermal diffusivity

$$\frac{\partial T}{\partial t} = \alpha \nabla^2 T \quad \longrightarrow \quad \alpha = \frac{k}{\rho C_p}$$

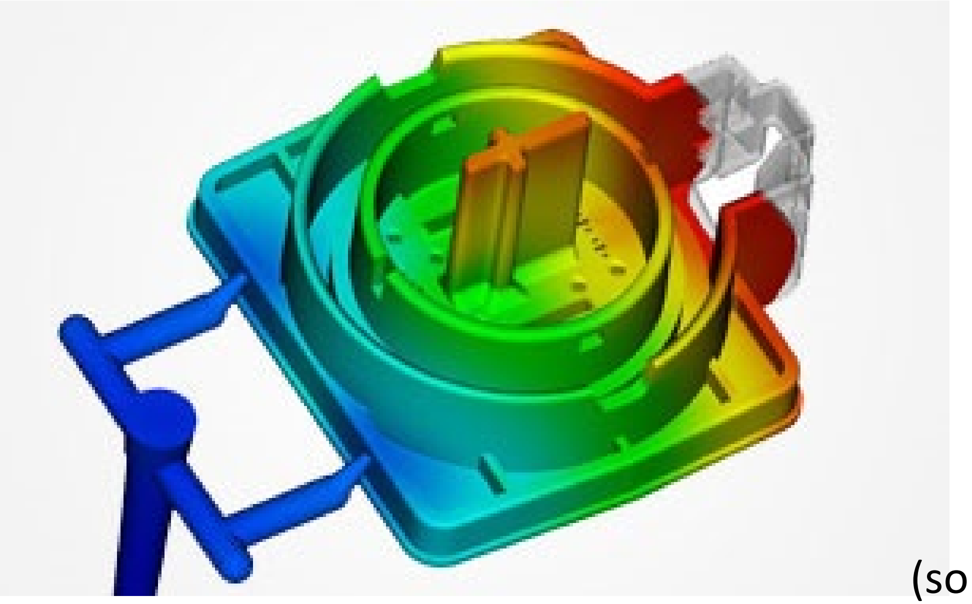
k *thermal conductivity - W/(m·K)*
Cp *specific heat capacity - J/(kg·K)*
ρ *density (kg/m³).*



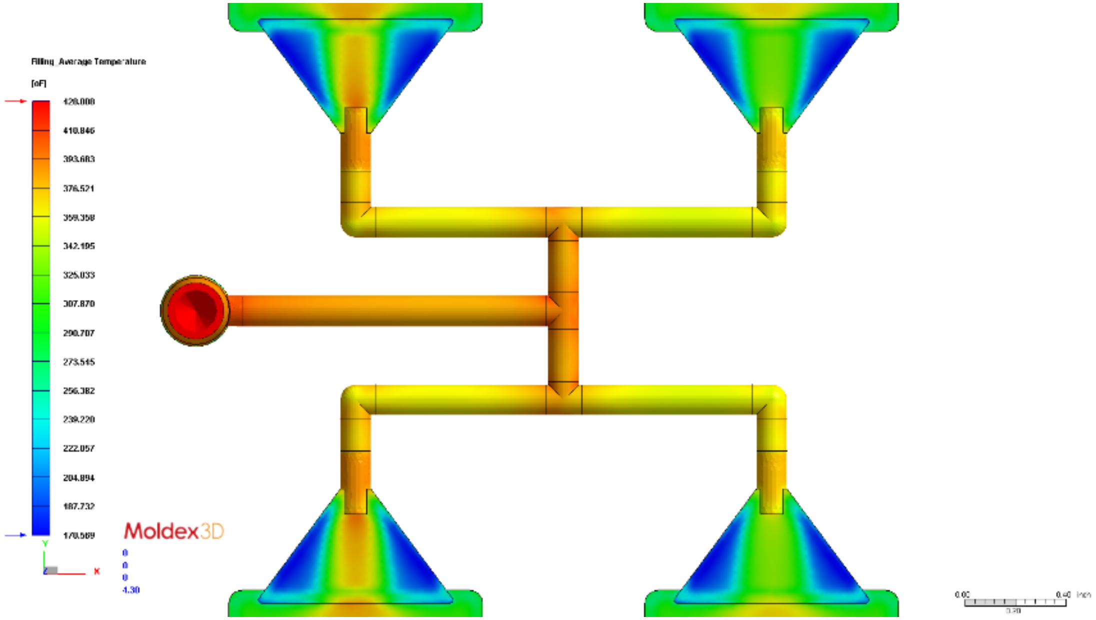
- Die casting
- Sand casting
- Injection molding

Thermal analysis

- Chvorinov’s model assumptions
  - One d model
  - Mold and metal have constant density, heat capacity, heat conductivity.
  - Metal has similar thermal properties in liquid and solid phase.
- Note that molding flow and temperature are nowadays simulated with CAD software.



(source: Moldex)



Cooling time (Chvorinov's rule)

Use to estimate solidification time

$$t = B\left(\frac{V}{A}\right)^n$$

Constant / usually 2...

Volume solidifying

Surface solidifying

$$B = \left[\frac{\rho_m L}{(T_m - T_o)}\right]^2 \left[\frac{\pi}{4k\rho c}\right] \left[1 + \left(\frac{c_m \Delta T_s}{L}\right)^2\right]$$

T_m = melting or freezing temperature of the liquid (in Kelvin)
T_o = initial temperature of the mold (in Kelvin)
$\Delta T_s = T_{pour} - T_m$ = superheat (in Kelvin)
L = latent heat of fusion (in $[J \cdot kg^{-1}]$)
k = thermal conductivity of the mold (in $[W \cdot m^{-1} \cdot K^{-1})]$)
ρ = density of the mold (in $[kg \cdot m^{-3}]$)
c = specific heat of the mold (in $[J \cdot kg^{-1} \cdot K^{-1}]$)
ρ_m = density of the metal (in $[kg \cdot m^{-3}]$)
c_m = specific heat of the metal (in $[J \cdot kg^{-1} \cdot K^{-1}]$)

Application of Chvorinov's rules

- Typical use is to ensure that **the riser** cools **after** the **casting**
- Typical rule of thumbs:

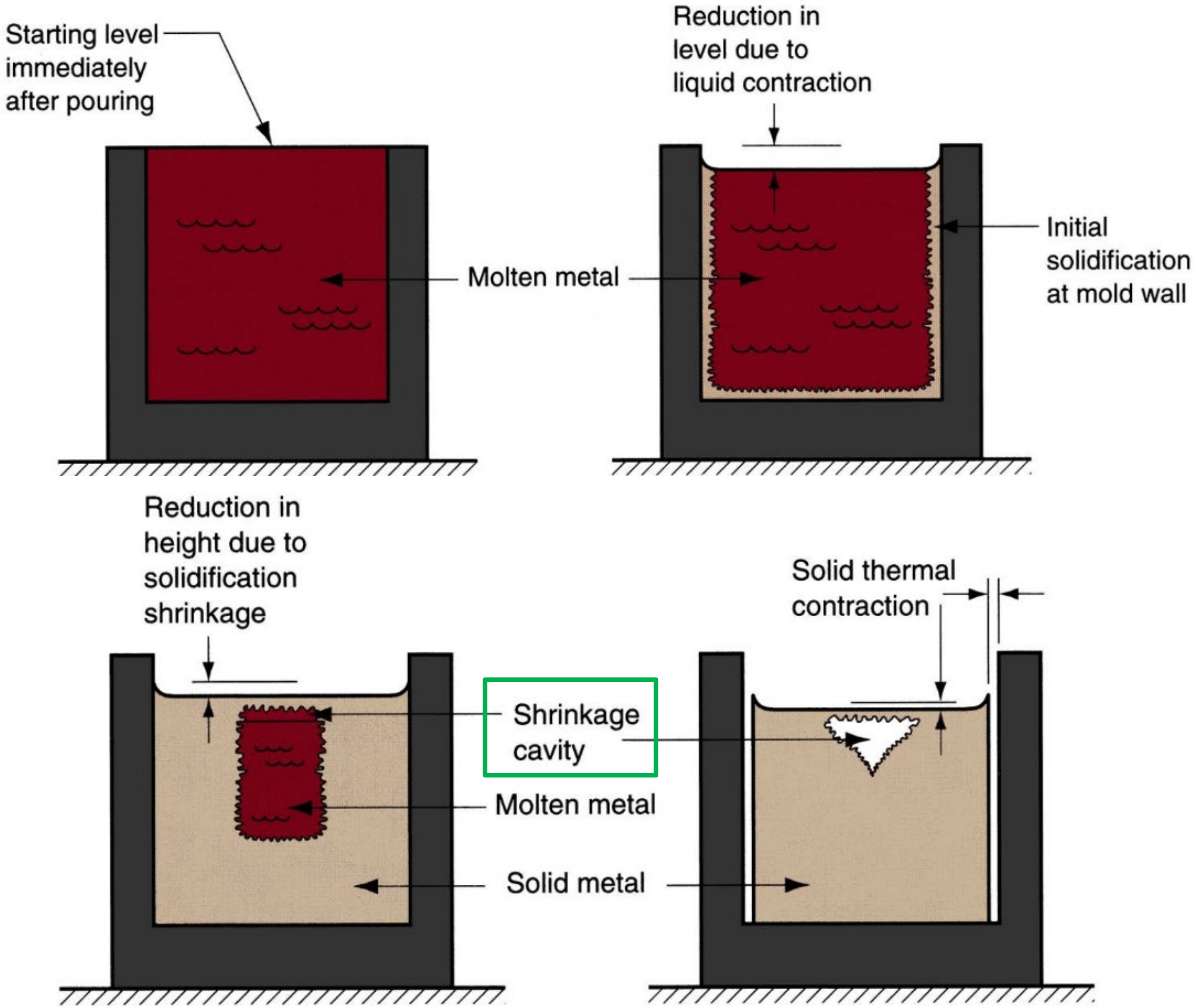
$$\left(\frac{V_{riser}}{A_{riser}}\right)^n \approx 1.25\left(\frac{V_{casting}}{A_{casting}}\right)^n$$

Solidification shrinkage

- For most materials, when solidification occurs, their volume shrinks
- Solidification process is a dynamic effect that can lead to undesired effect if not controlled

Concept of directional solidification

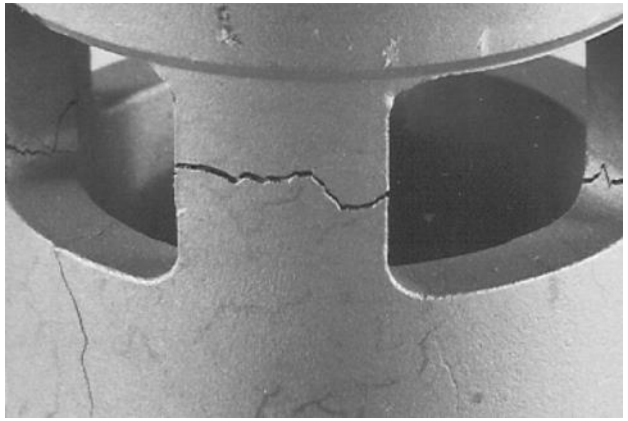
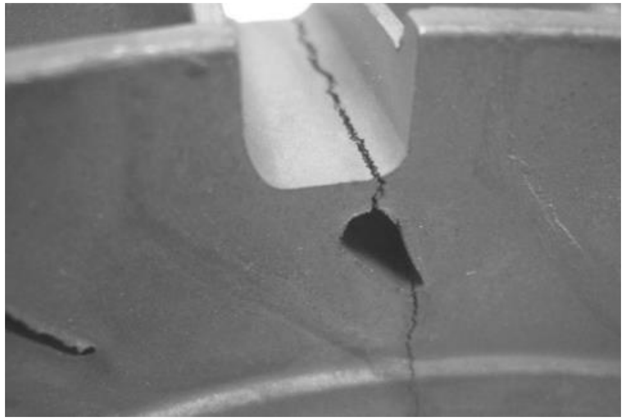
(Note that dimensions are exaggerated for the sake of understanding)

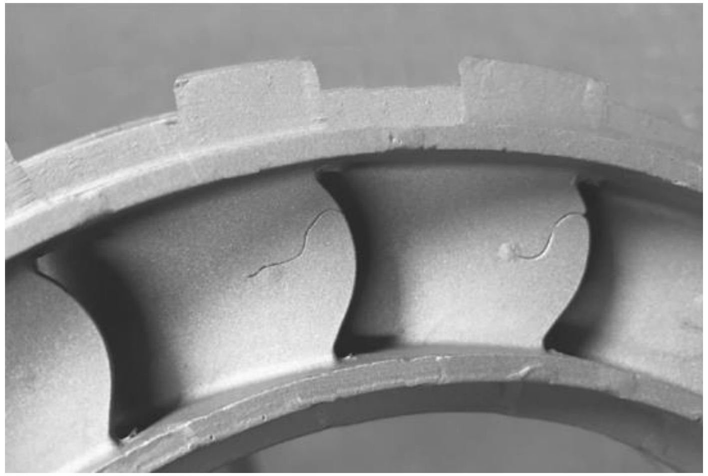


Illustrations adapted from Seok-min Kim (Cung-An Univ.), lecture notes

Typical casting defects

- Shrinkage, fractures
- Impurities
- Pouring defects
  - *Misruns:* metal does not completely fill the cavity
  - *Cold-shuts:* 'cold welding'
- Gas bubbles
  - Gas trapped in the liquid form cannot escape during solidification (typ. H_2, O_2, N_2)

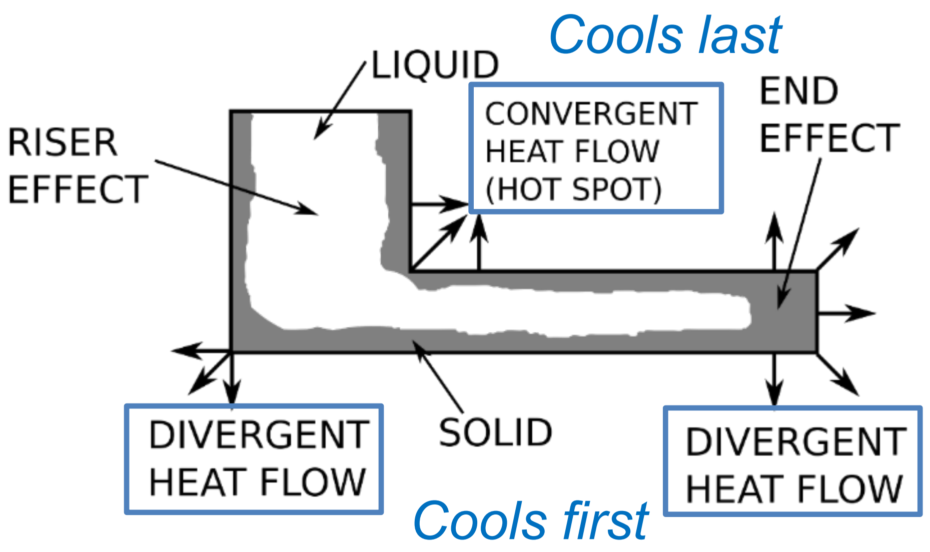



'Atlas of possible defects'
https://61746c6173.investmentcasting.org/casting/defects/index.html

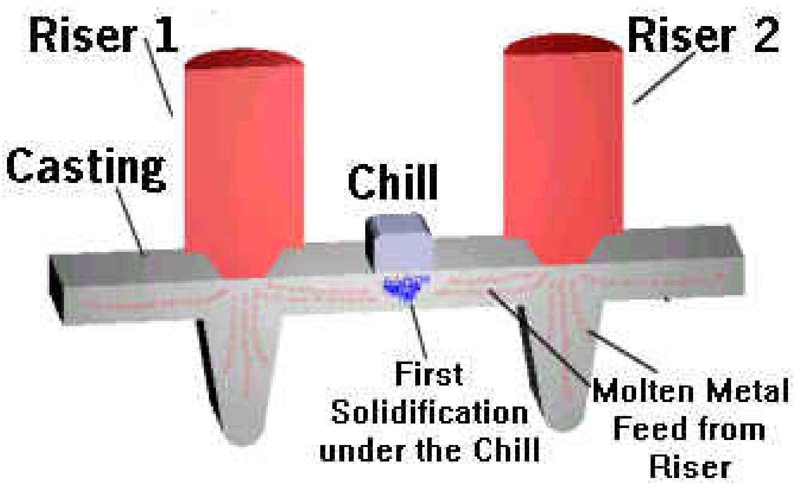
(Illustrations / Investment Casting Institute)

Directional solidification

- Geometries introduce **anisotropic temperature distributions**
- **Solidification** does not start at the same time everywhere

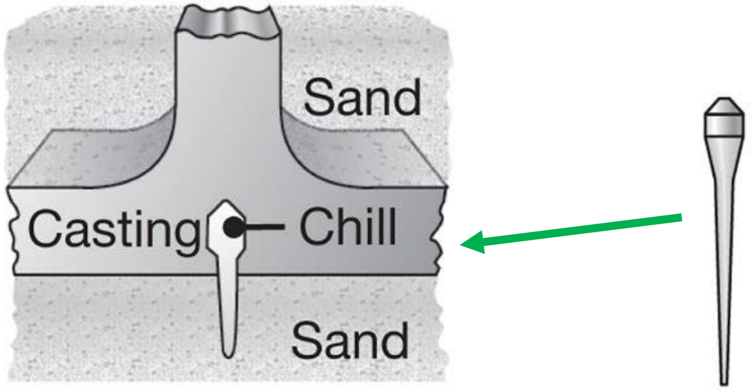


(source adapted from Wiki)



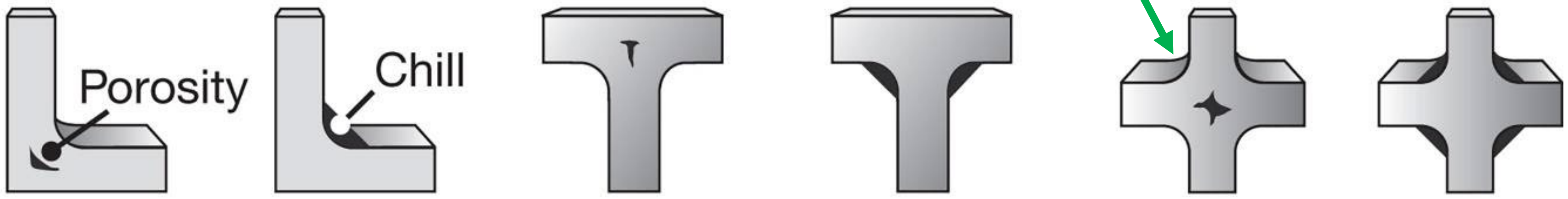
- Goal is to control a **temperature gradient to force directional solidification**
- This can be done by disposing **chillers** ('Voleur de chaleur') at certain locations to force the solidification to start at a specific point

Example of technical solution for controlling solidification ('chills') / Directional solidification



Chillers are pieces with various geometries made of material with good calorific properties as 'heat absorbers'

Defect due to non uniform cooling

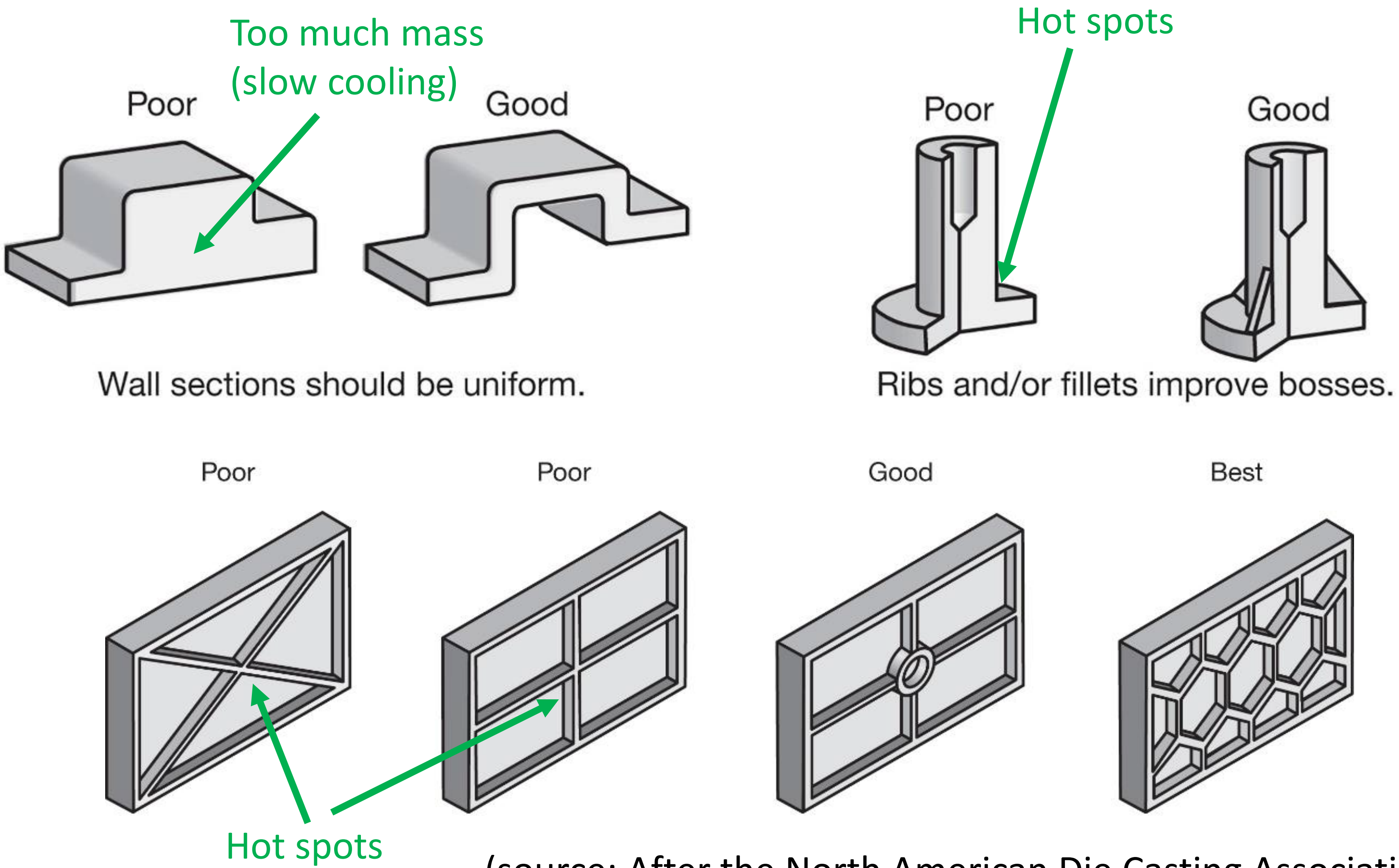


(b)

Defect due to non uniform cooling

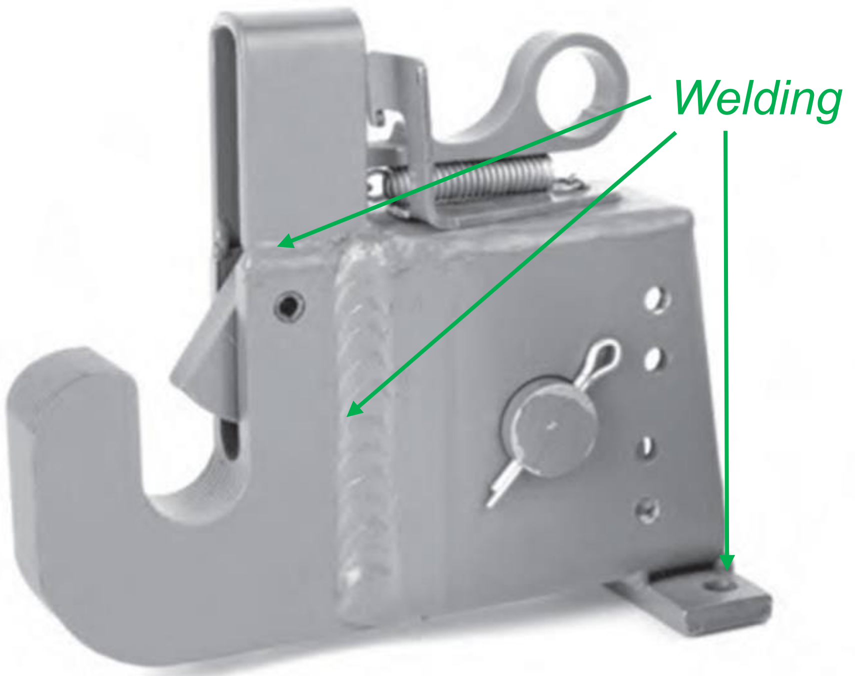
(source: S. Kalpakjian, Manufacturing, Pearson Ed.)

Example of corrective actions through mold design (empiric) principles

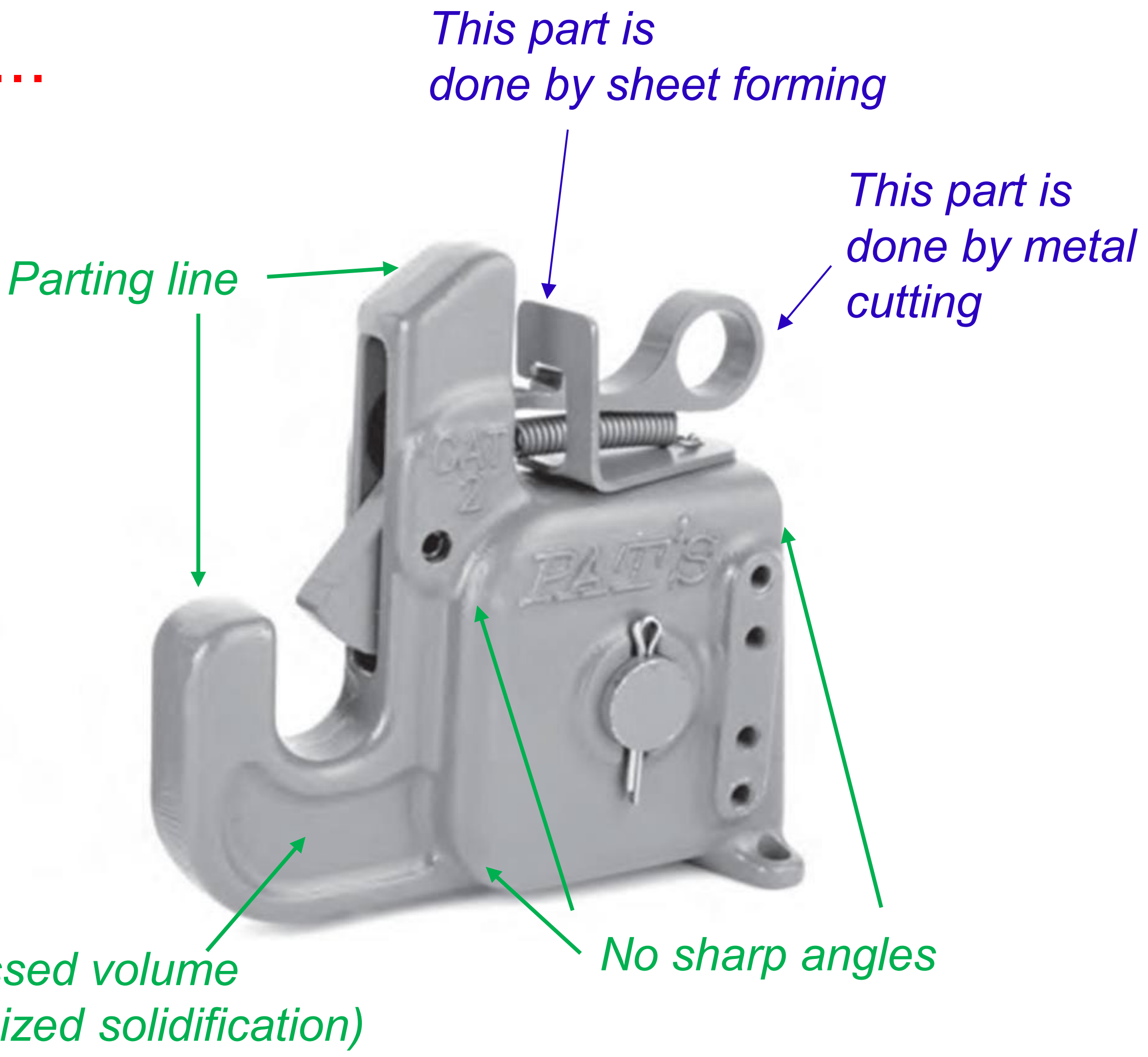


(source: After the North American Die Casting Association
S. Kalpakjian, Manufacturing, Pearson Ed.)

Example of a part redesigned from one manufacturing principle to the other...



Housing made by **welding** and **assembly** of **five** components produced by metal forming



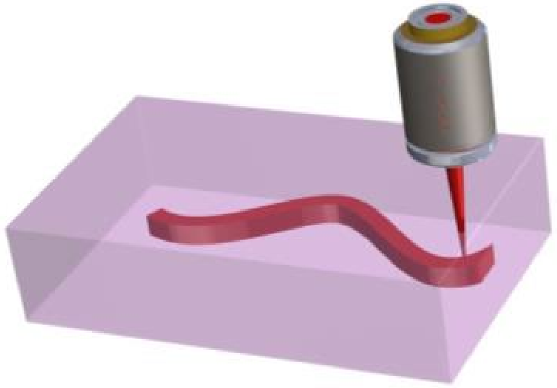
Sand casted equivalent (**one** part only for the housing)

Part III / Illustrative example of ongoing research at EPFL

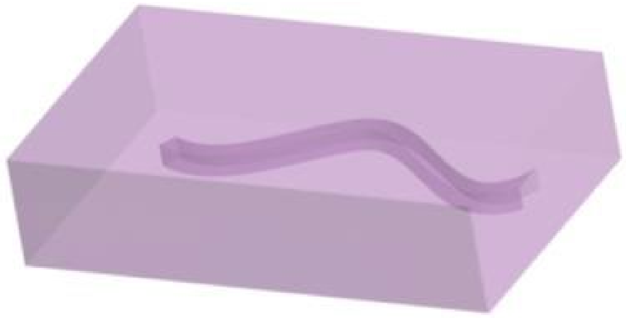
(Galatea Lab / Laboratory of Mechanical Metallurgy)

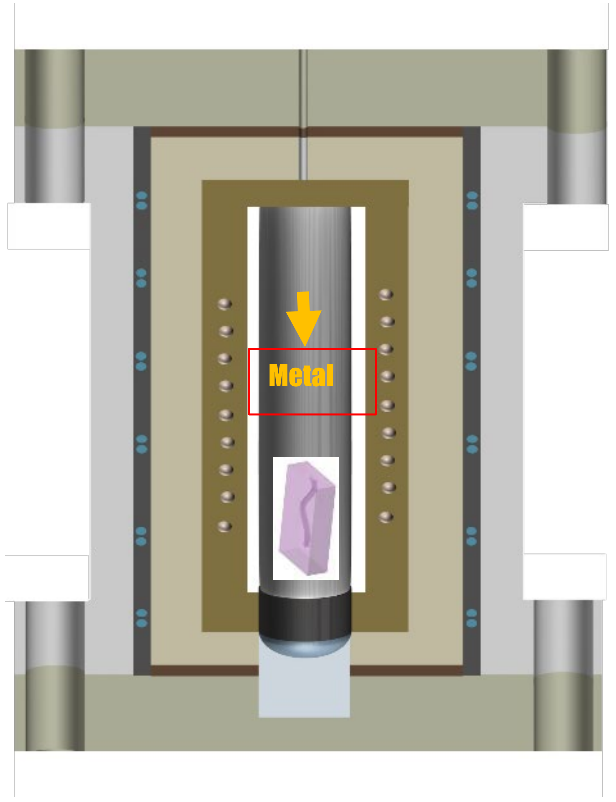
Basic idea

Step 1 / Femtosecond laser exposure



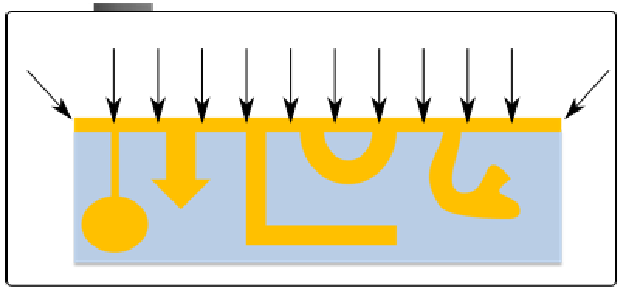
Step 2 / Etching step





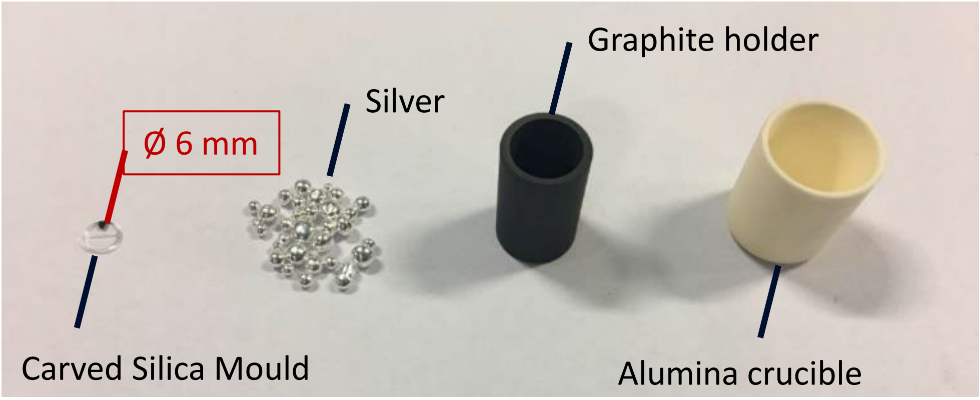
Step 3 / Pressurized metal infiltration under vaccuum

3D-micro-casting: Process



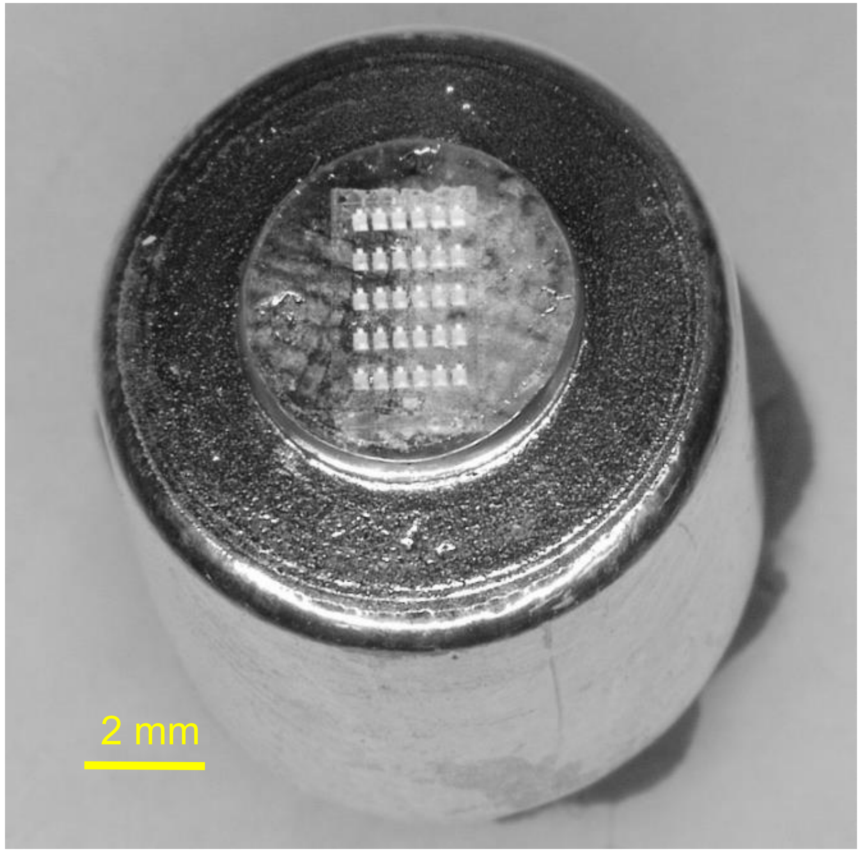
Step [illegible]
[illegible] chamber (1 mBar)

Enables the freeform fabrication of **3D** complex metal micro-parts with the potential for **sub-micron** resolution

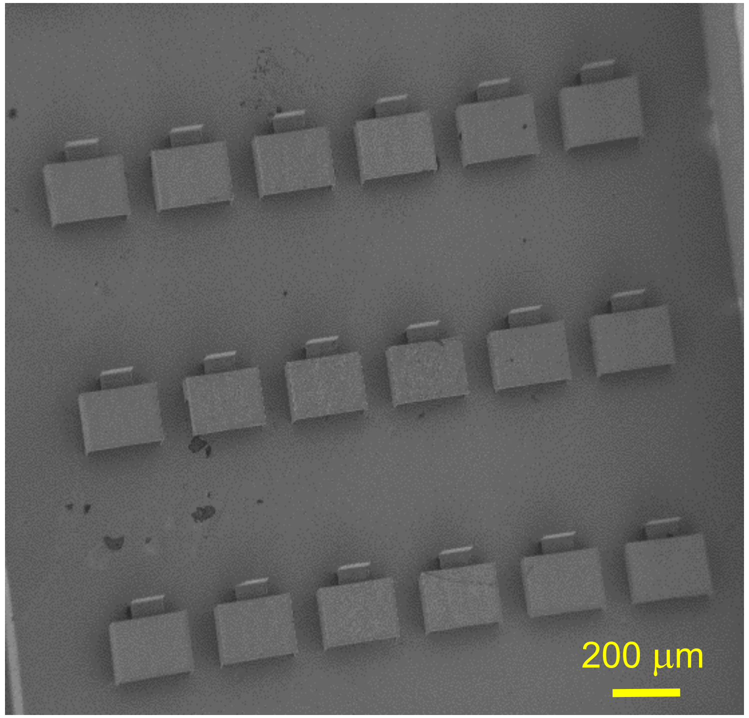


L. Borasi, E. Casamenti, R. Charvet, C. Dénéréaz, S. Pollonghini, L. Deillon, T. Yang, F. Ebrahim, A. Mortensen, and Y. Bellouard, "3D metal freeform micromanufacturing," Journal of Manufacturing Processes ***68****, 867–876 (2021).*

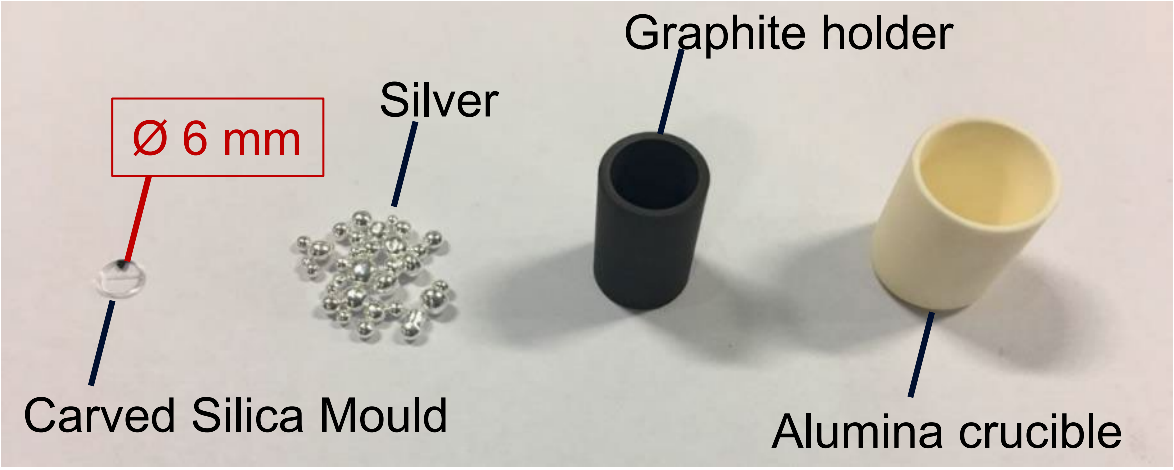
Combine metal infiltration and femtosecond laser glass 3D machining

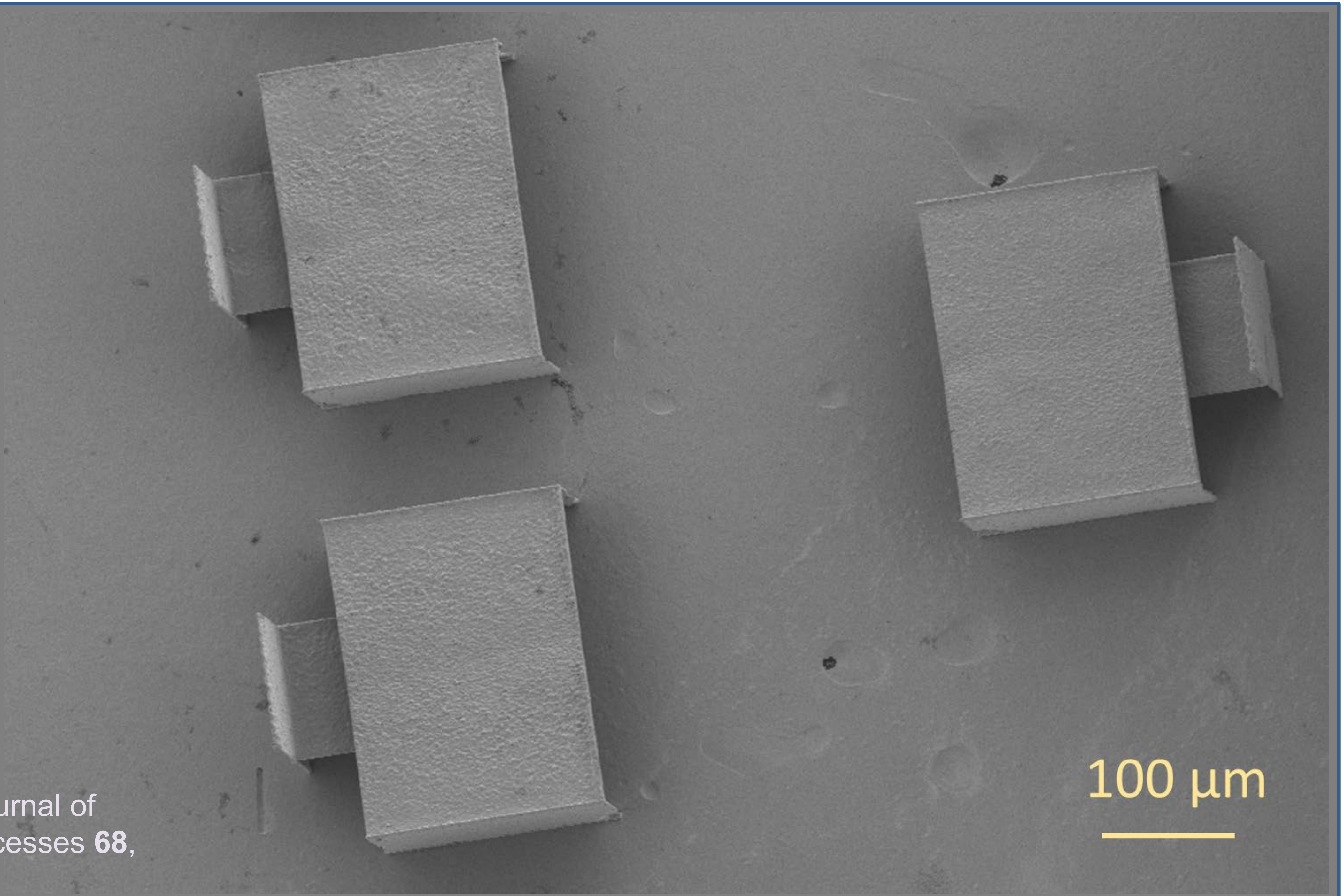


SEM view (substrate removed)



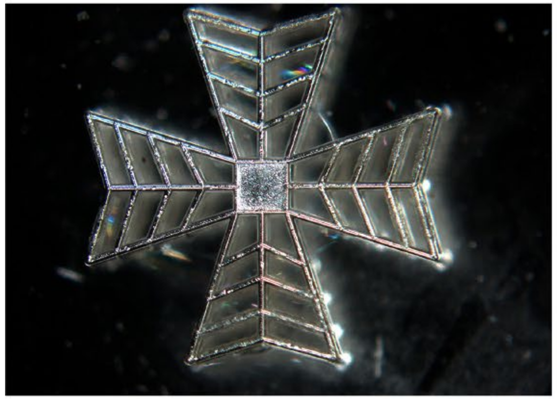
Substrate infiltration

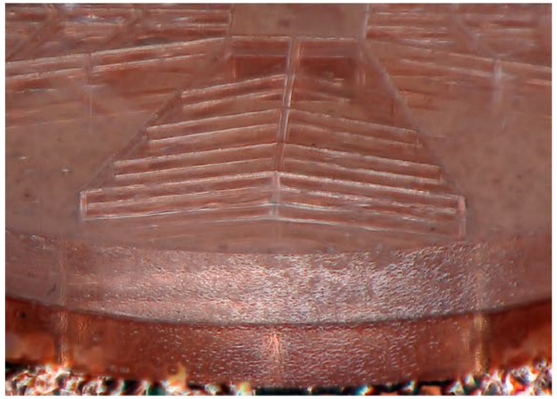


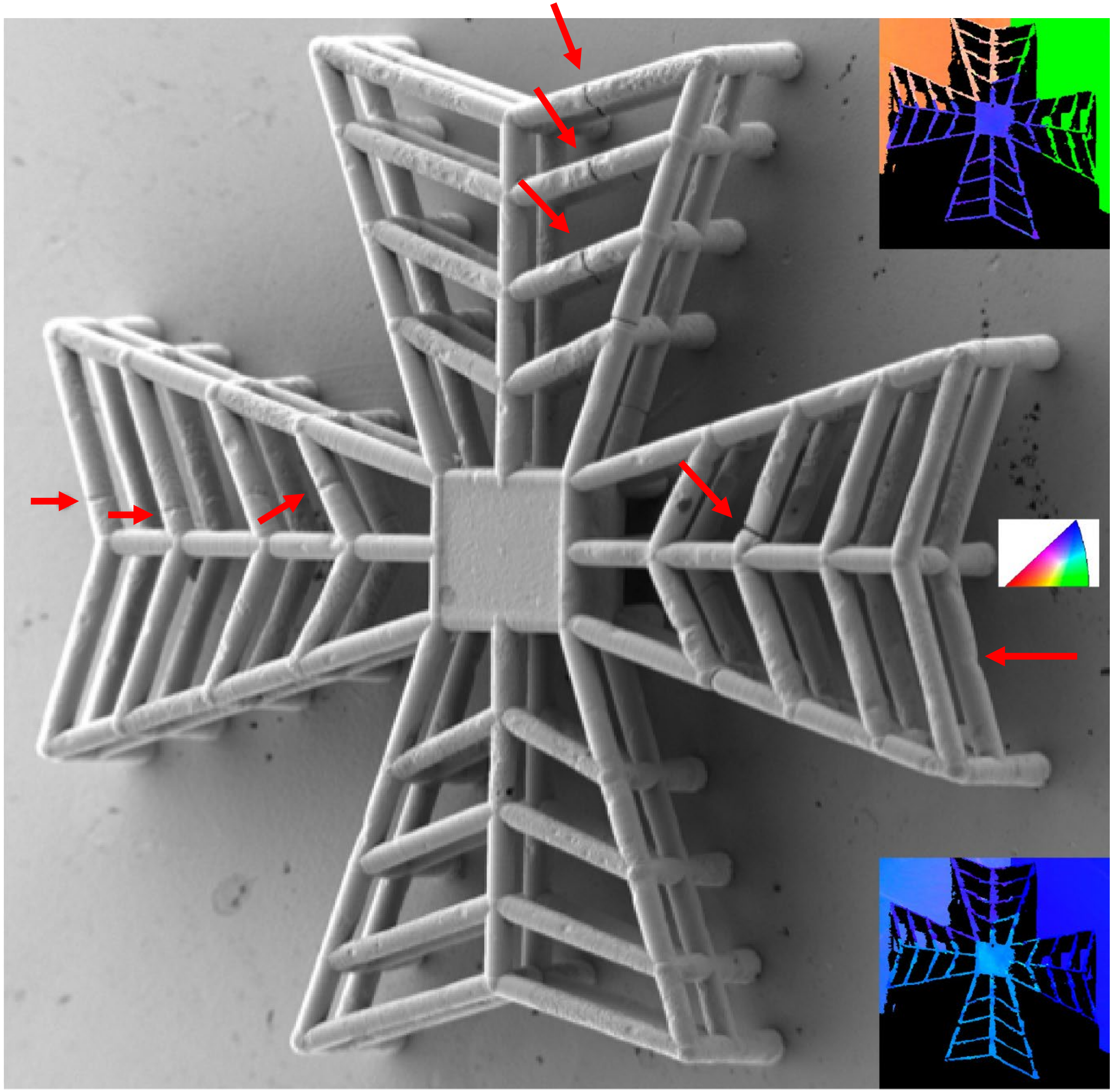


L. Borasi, et al., Journal of Manufacturing Processes **68**, 867–876 (2021).

Illustration



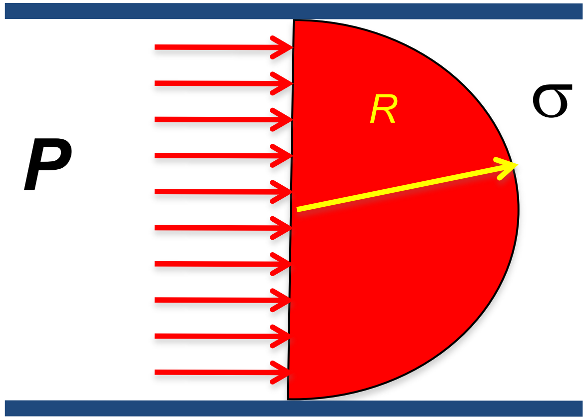




Scaling effect in casting

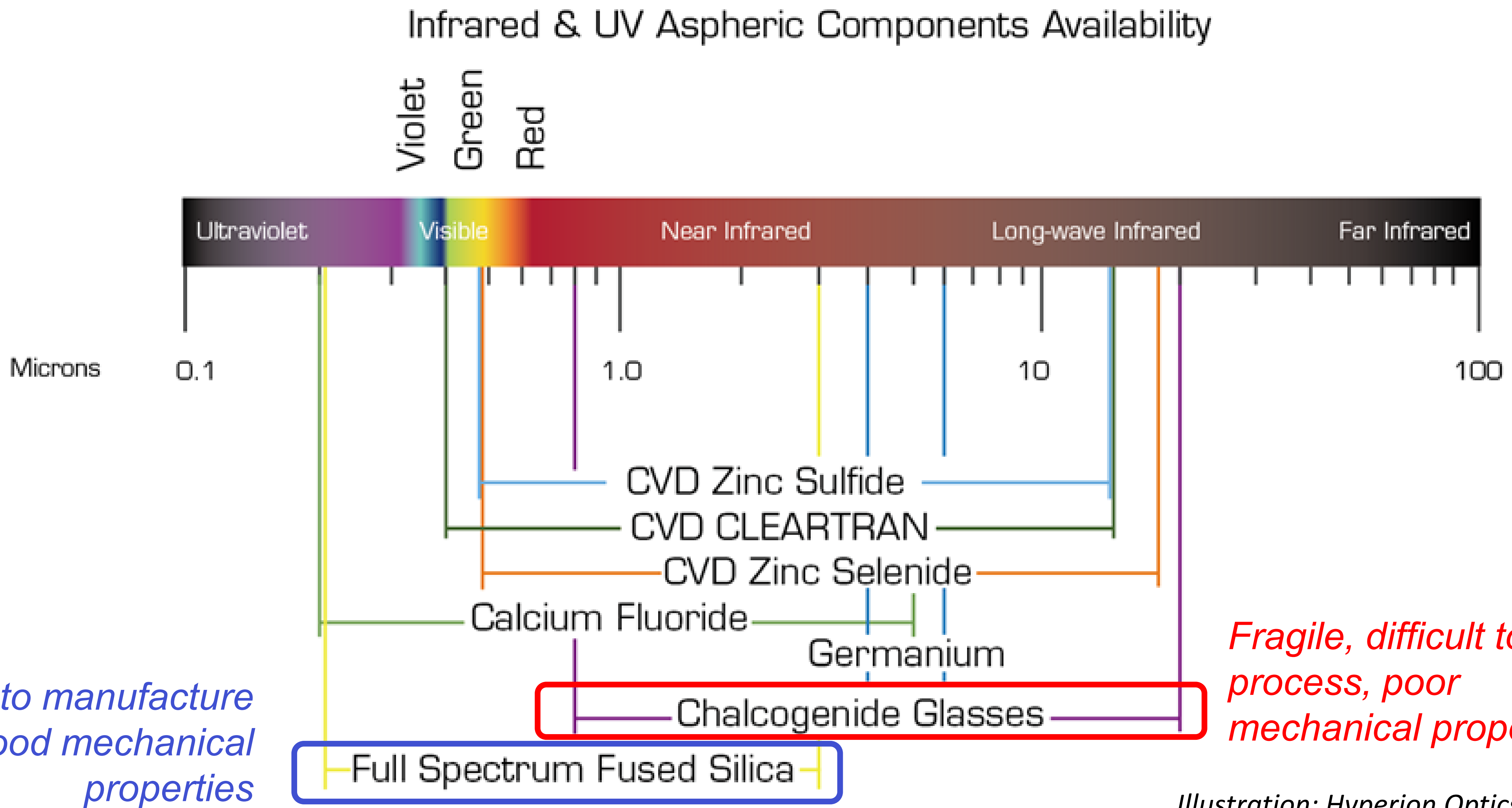
- **High aspect ratio** (>1:100), **3D** cavities with **sub-micron** resolution in **a high melting point** (>1200 deg. C) substrate
- Surface tension ($\sigma \approx 1$ J . m^{-2}) of **metals** requires **10 MPa** to infiltrate features down to **100 nm** ($P \approx \sigma/R$)

$P \approx R^{-1}$ MPa
if R is in µm



*Combining femtosecond laser machining with pressure infiltration has the potential to produce **3D metal parts** with **0.1 µm** feature resolution*

IR glass into silica: the best of both world...

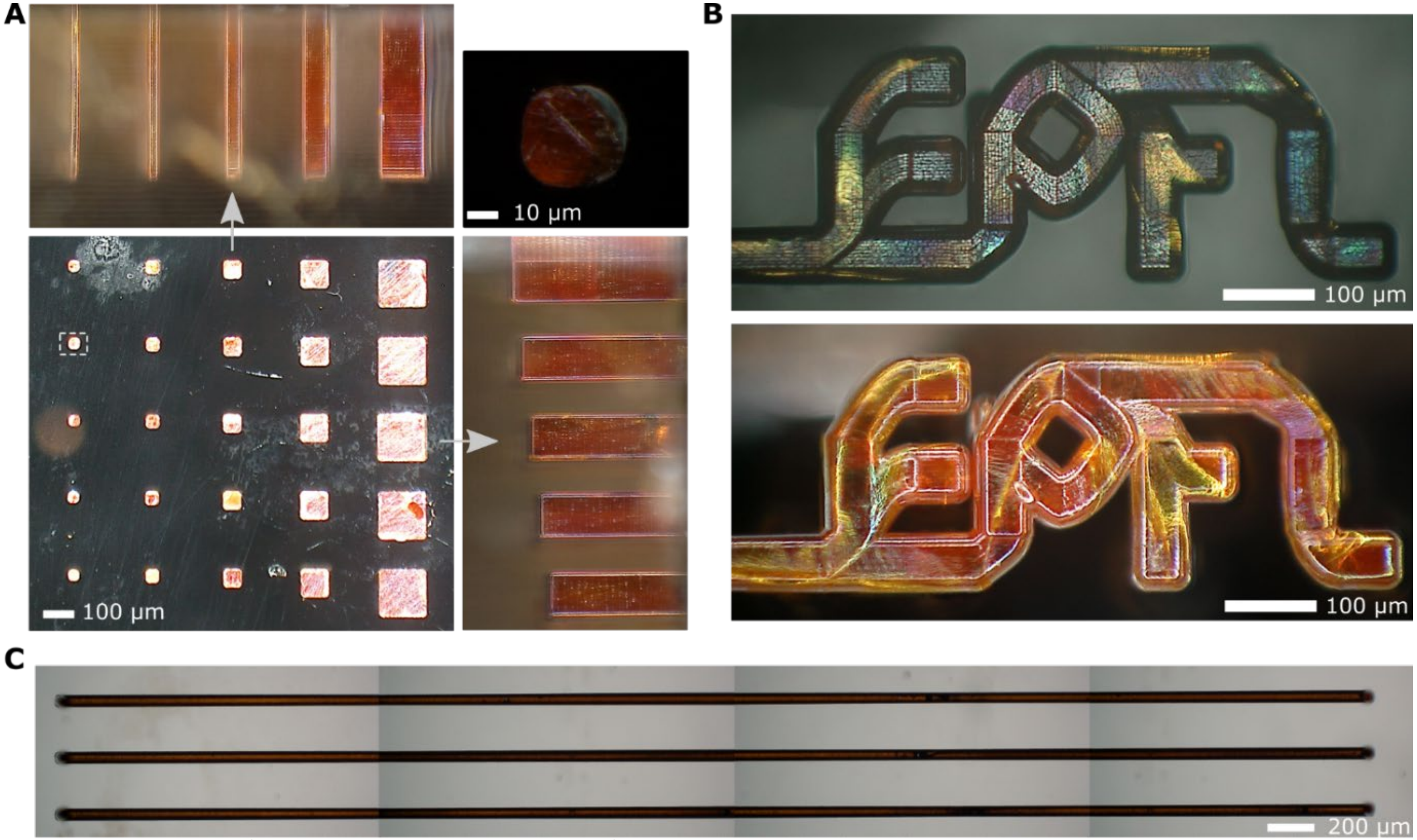


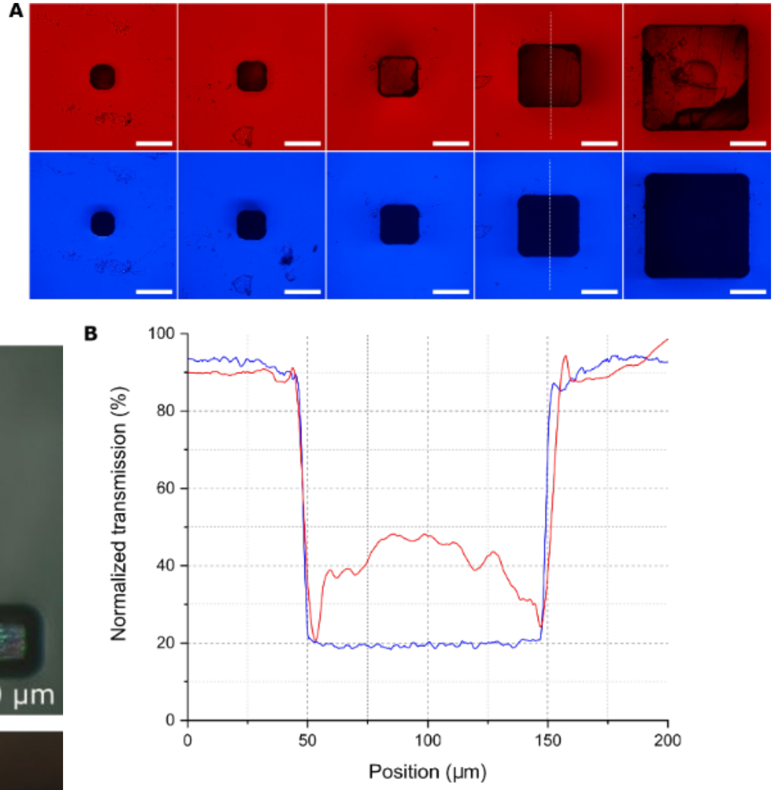
Easy to manufacture Good mechanical properties

Fragile, difficult to process, poor mechanical properties...

Illustration: Hyperion Optics

Illustration:
Chalcogenide glass into silica





E. Casamenti, G. Torun, L. Borasi, M. Lautenbacher, M. Bertrand, J. Faist, A. Mortensen, and Y. Bellouard, "Glass-in-glass infiltration for 3D micro-optical composite components," Opt. Express **30**, 13603 (2022).

Wrap-up / Things to remember

- The three main types of casting methods:
  - Sand casting
  - Lost-wax
  - Dye casting
  - Metal injection molding (MIM) process
- Solidification process
  - Solidification front
  - Solidification shrinkage
  - Chvorinov’s rule
- An illustration of the link between design and manufacturing

'Lexique manufacturing'

English (UK) > French

- Casting of metals: *Coulage des métaux*
- Gating systems: *système de remplissage*
- Sand casting: *Moulage au sable*
- Lost-wax casting: *Moulage à la cire perdue*
- Dye casting: *Injection des métaux*
- Chill: *Voleur de chaleur*
- Dendrite: *Dendrite*
- Riser: *Masselotte*
- Metal Injection Molding: *Moulage par injection des métaux*
- Sprue: Carotte de coulée, carotte d'injection
- Runner: Canal chaud