Casting

Process, Analysis and Equipment

Casting since about 5000-3000 BC

Ancient Greece; bronze statue casting circa 450BC

Left: Bronze statue of a man, Hellenistic period, mid-2nd-1st century B.C., H. 73 in (185.4 cm)
Below: Herakles (Son of Zeus)

Casting

Process, Analysis and Equipment

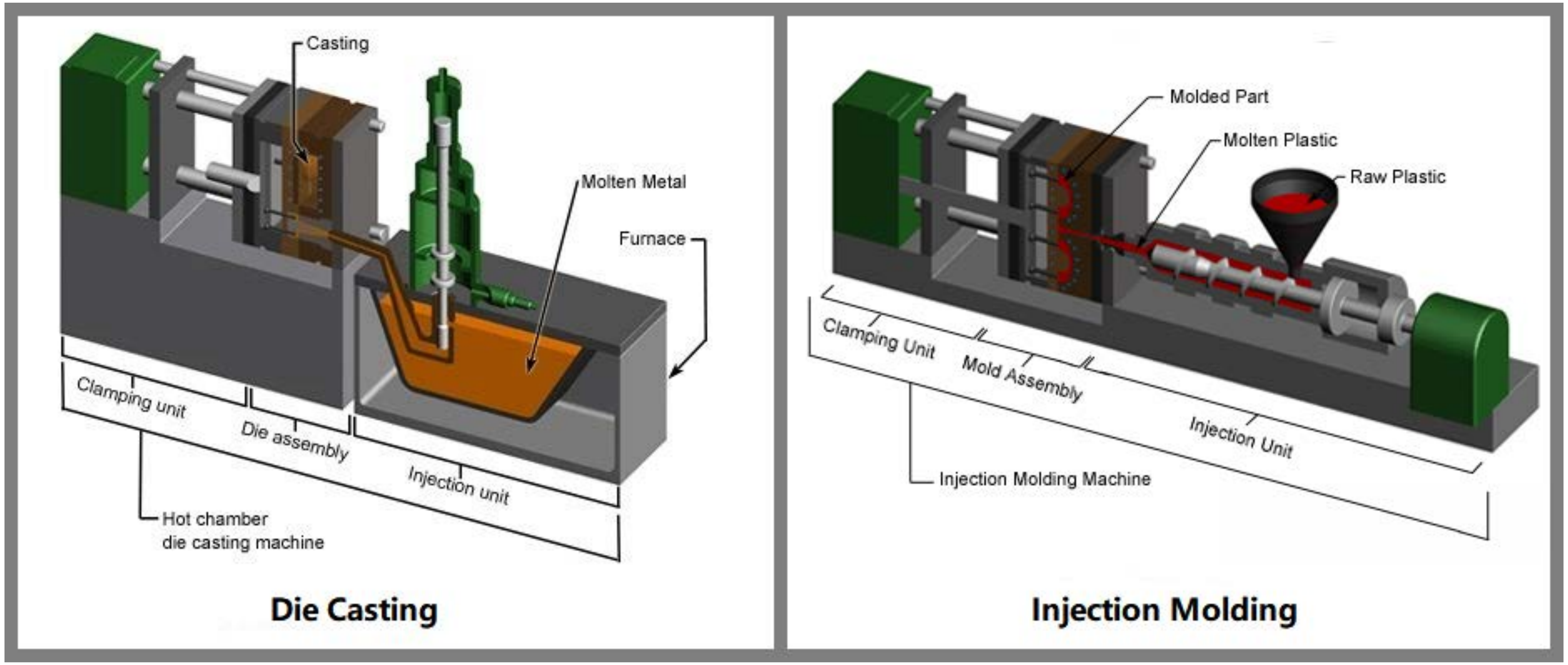
Casting Versatility

- many types of metals
- rapid production
- wide range of shapes and sizes
- complex parts as an integral unit

2.008 Topic Coverage

Process Steps

Sand Casting, Die Casting, Investment Casting, Lost Foam Casting



Phase Change, Shrinkage

Heat Transfer

Pattern Design

Additional Processes and Developments

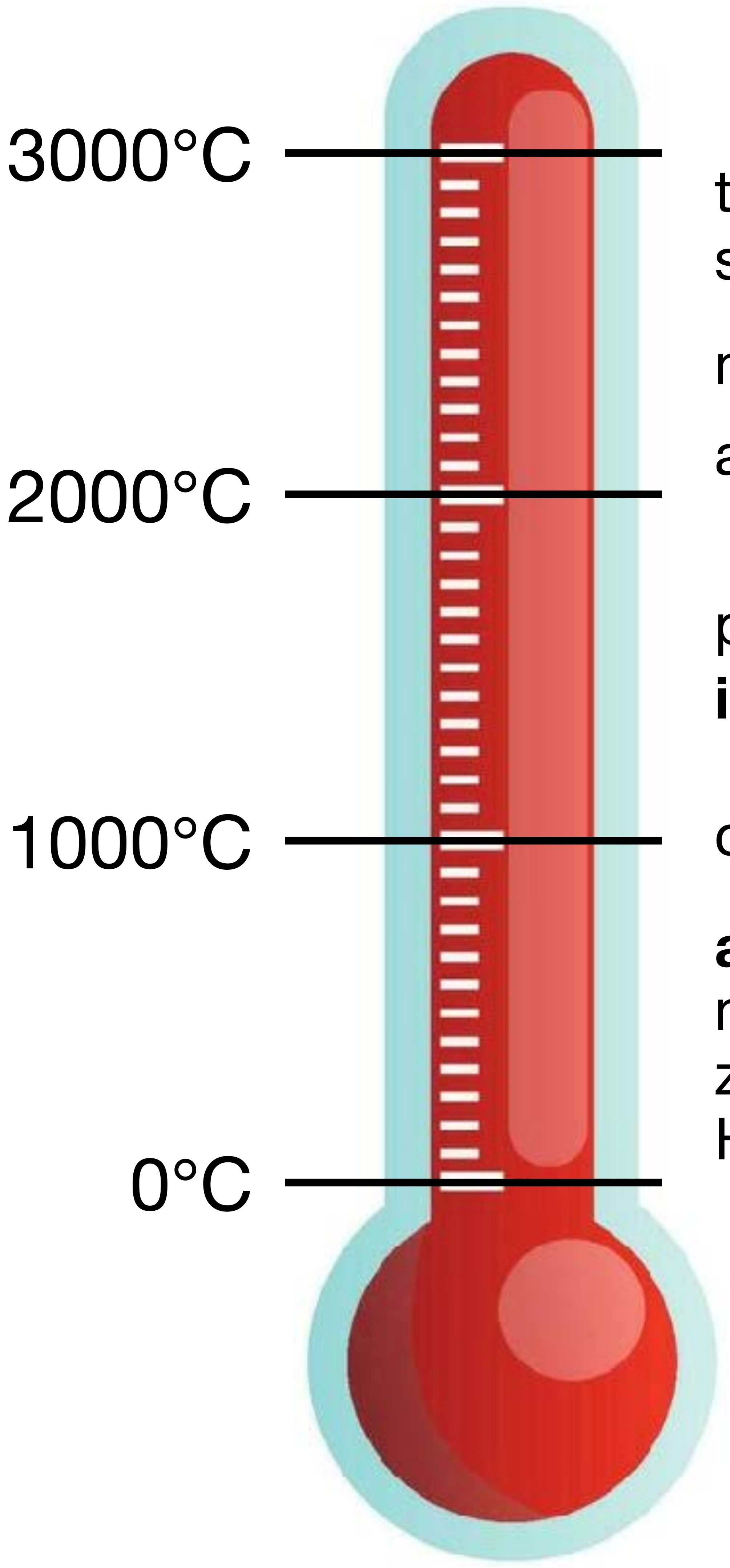
Physics and Constraints

Phase Change

- density
- solubility
- diffusion rates

High Melt Temperature

- chemical activity
- high latent heat
- handling
- outgassing



tungsten carbide
silicon carbide

molybdenum

alumina

platinum, titanium
iron and steels (1500°C), nickel

copper, bronze, brass

aluminum (660°C)
magnesium
zinc, tin
HDPE

Analysis

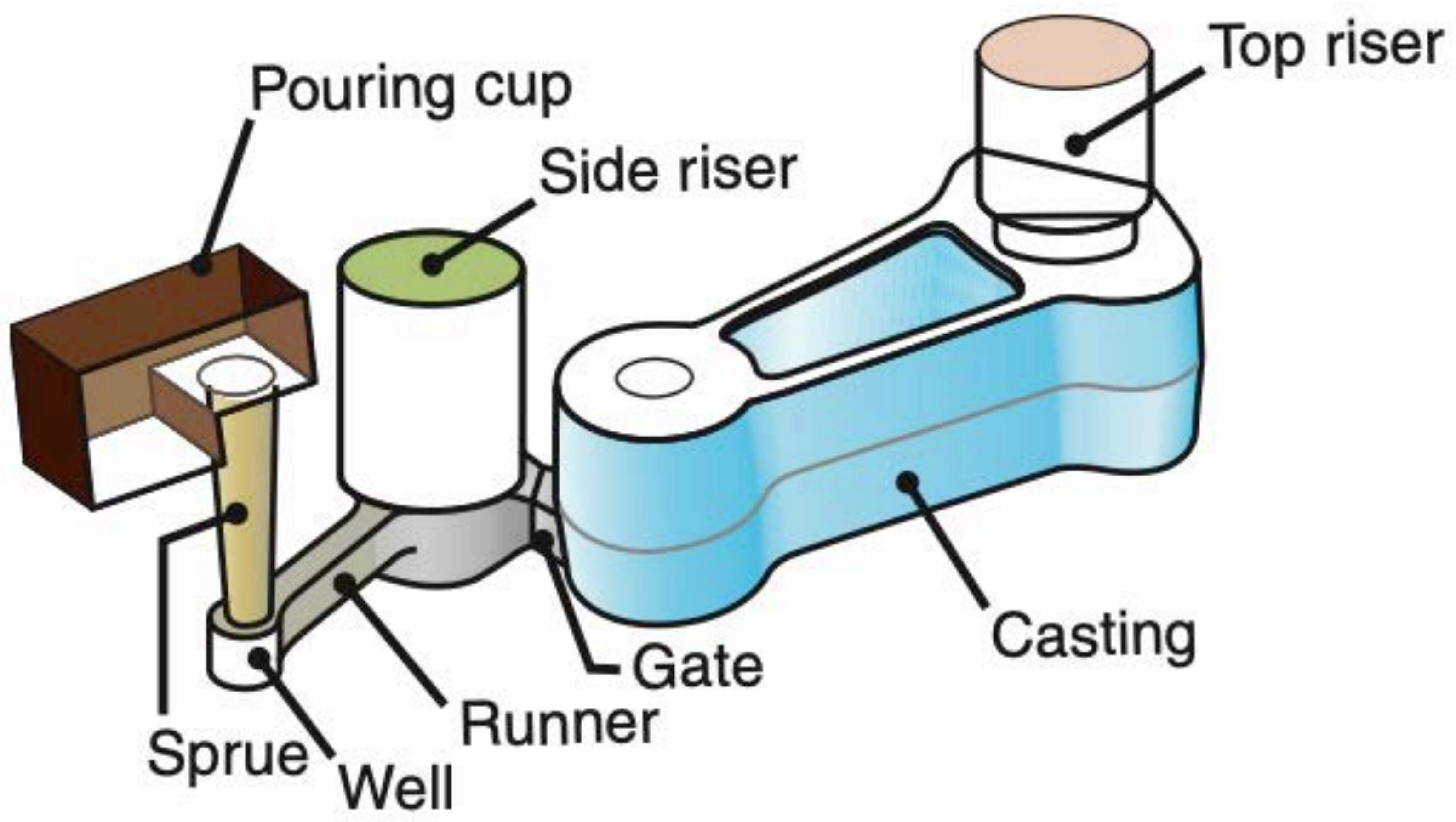
- fluid mechanics for mold filling
- heat transfer for solidification
- thermodynamics, mass transfer, heat transfer for nucleation and growth
- materials behavior for structure/property relationships

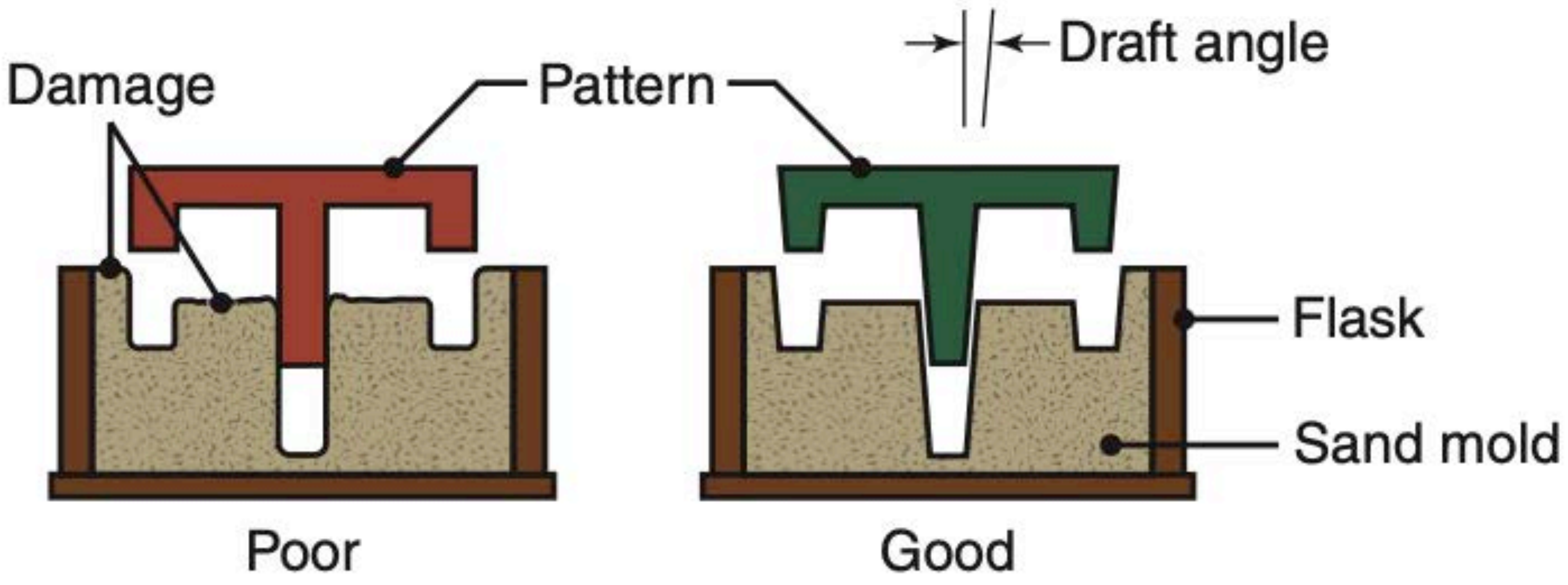
Sand Casting

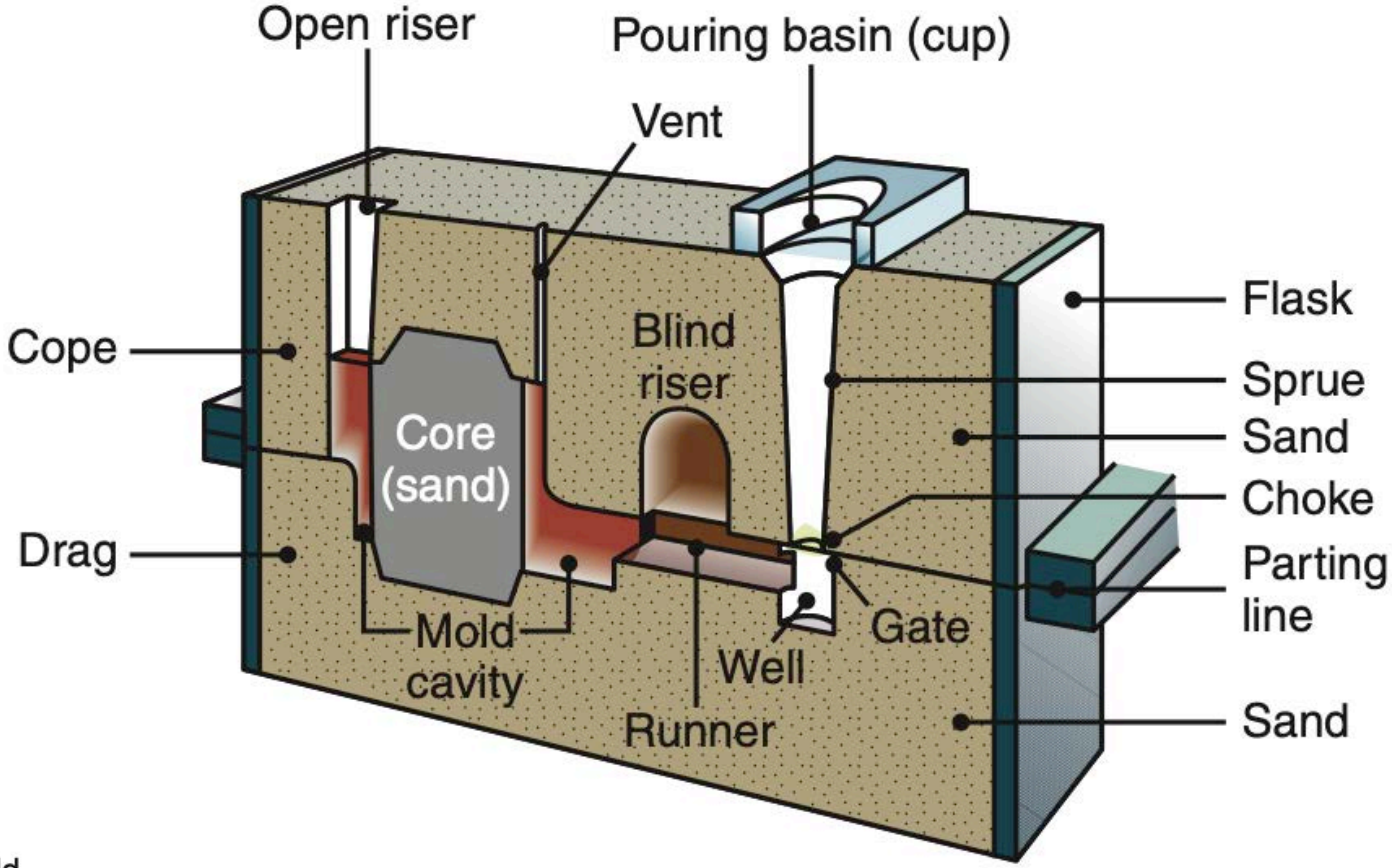
Process Steps (all casting methods)

- pattern/mold making
- melt preparation
- mold filling
- solidification/ cooling
- removal/ breakout/ secondary processing

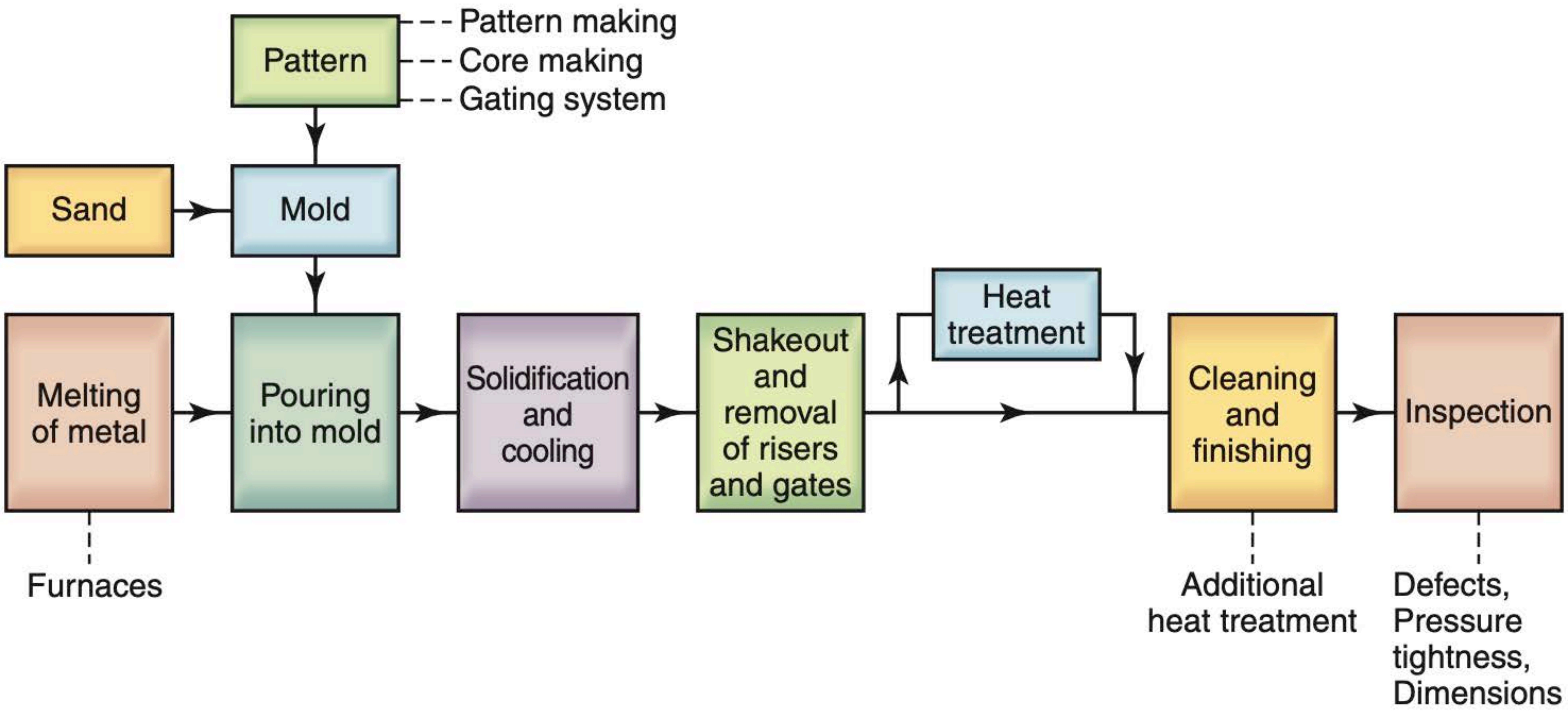
Sand Casting







Sand Casting



Sand Casting: Pattern Making

- shrinkage allowance
- machining allowance
- distortion allowance
- parting line
- draft angles

TABLE 12.1

Normal Shrinkage Allowance for Some Metals Cast in Sand Molds

Metal	Shrinkage allowance (%)
Cast irons	
Gray cast iron	0.83–1.3
White cast iron	2.1
Malleable cast iron	0.78–1.0
Aluminum alloys	1.3
Magnesium alloys	1.3
Copper alloys	
Yellow brass	1.3–1.6
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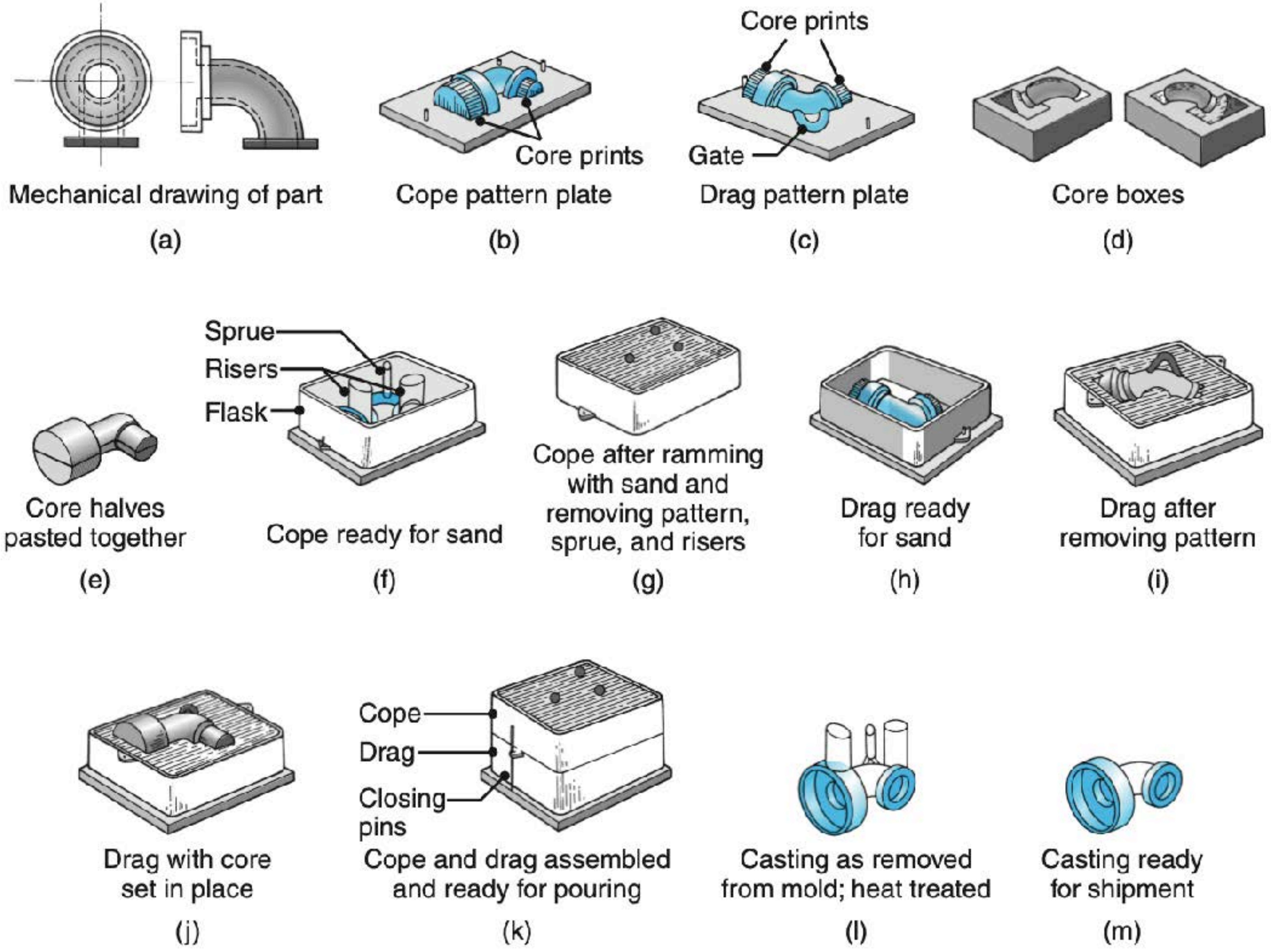


Sand Casting

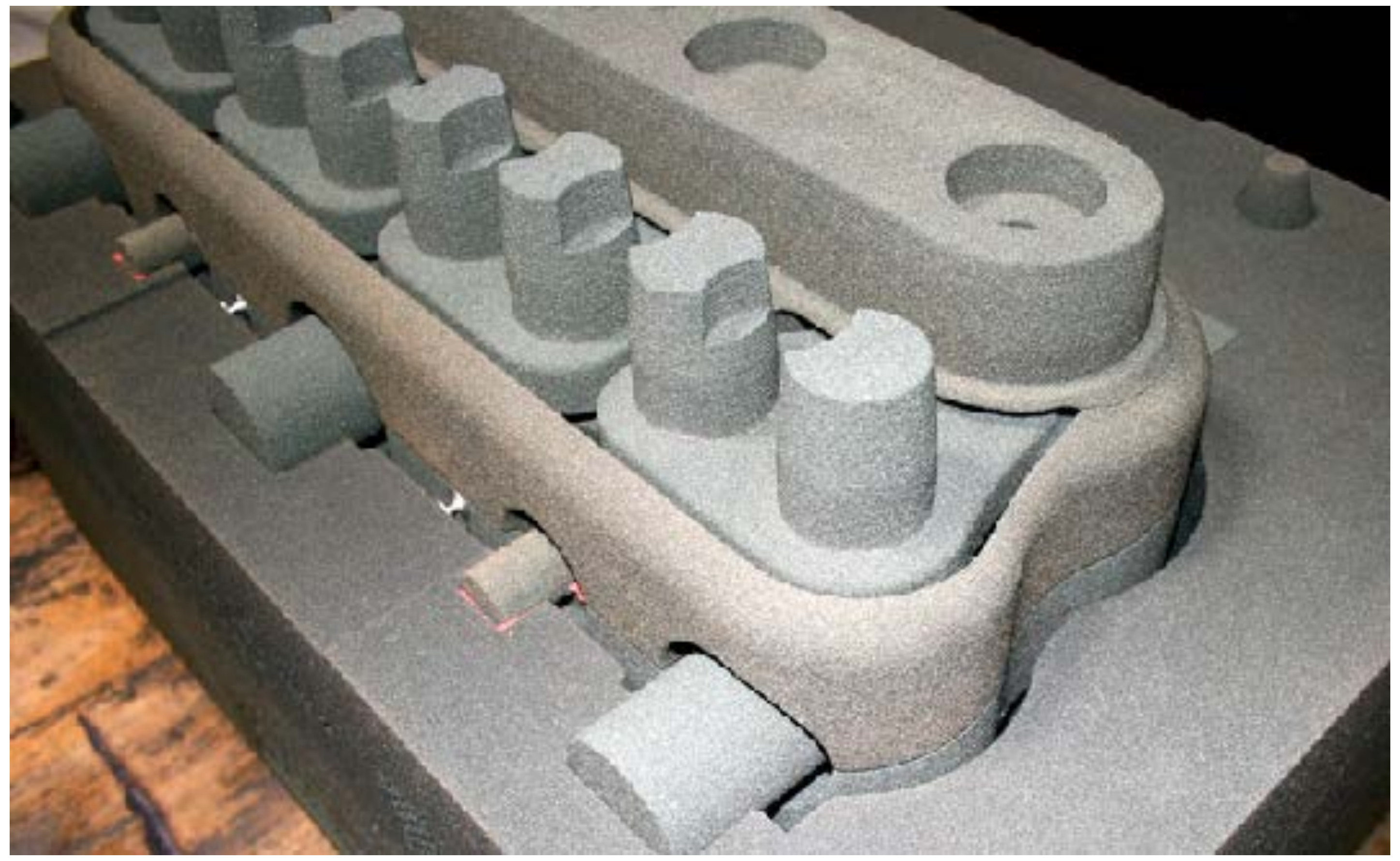
- low surface detail: post-machining for high tolerance parts

-low initial investment in tooling: very common, can make large parts

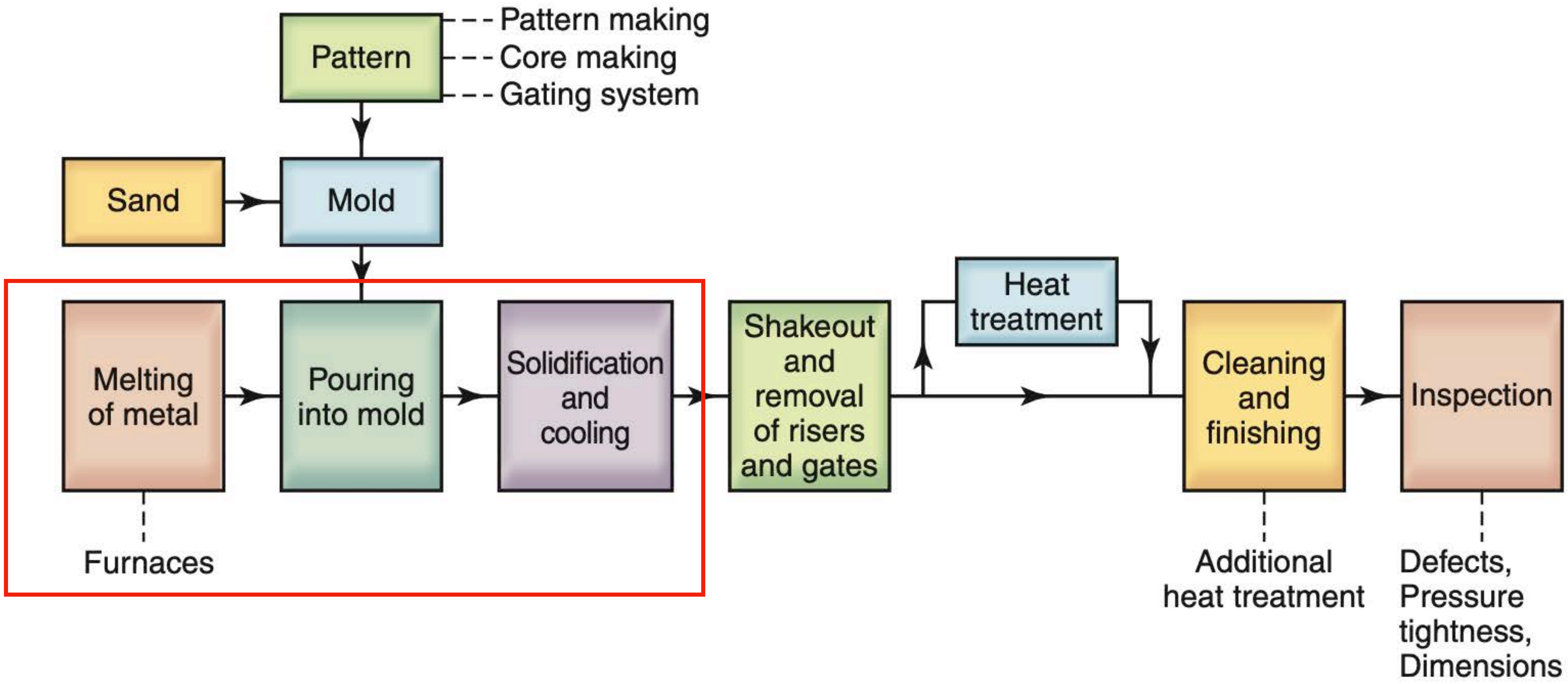
- flow is gravity-driven

-labor-intensive with a long cycle time

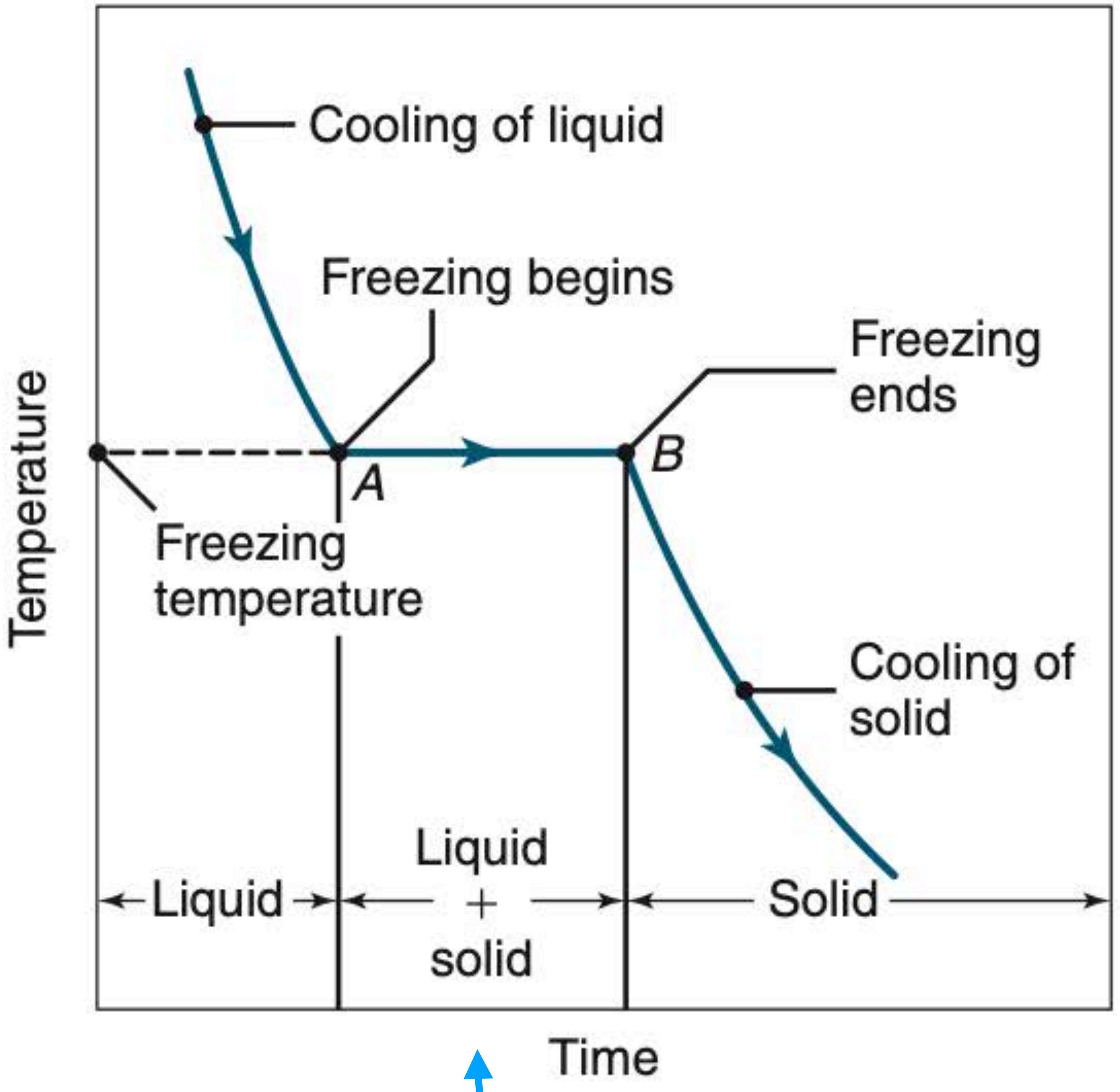
-3D printing of molds and complex cores can achieve previously impossible geometries



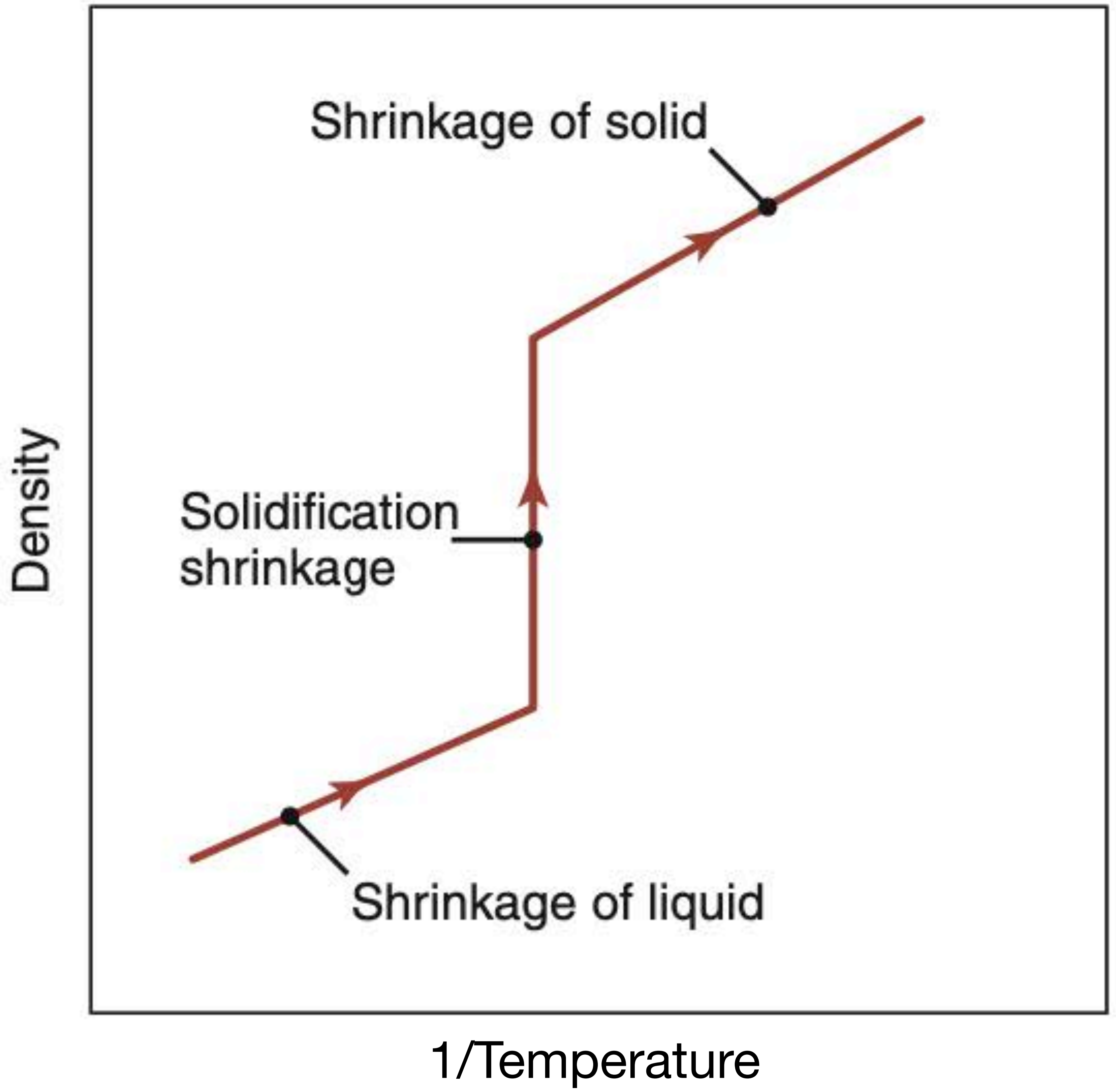
Sand Casting Physics



Solidification



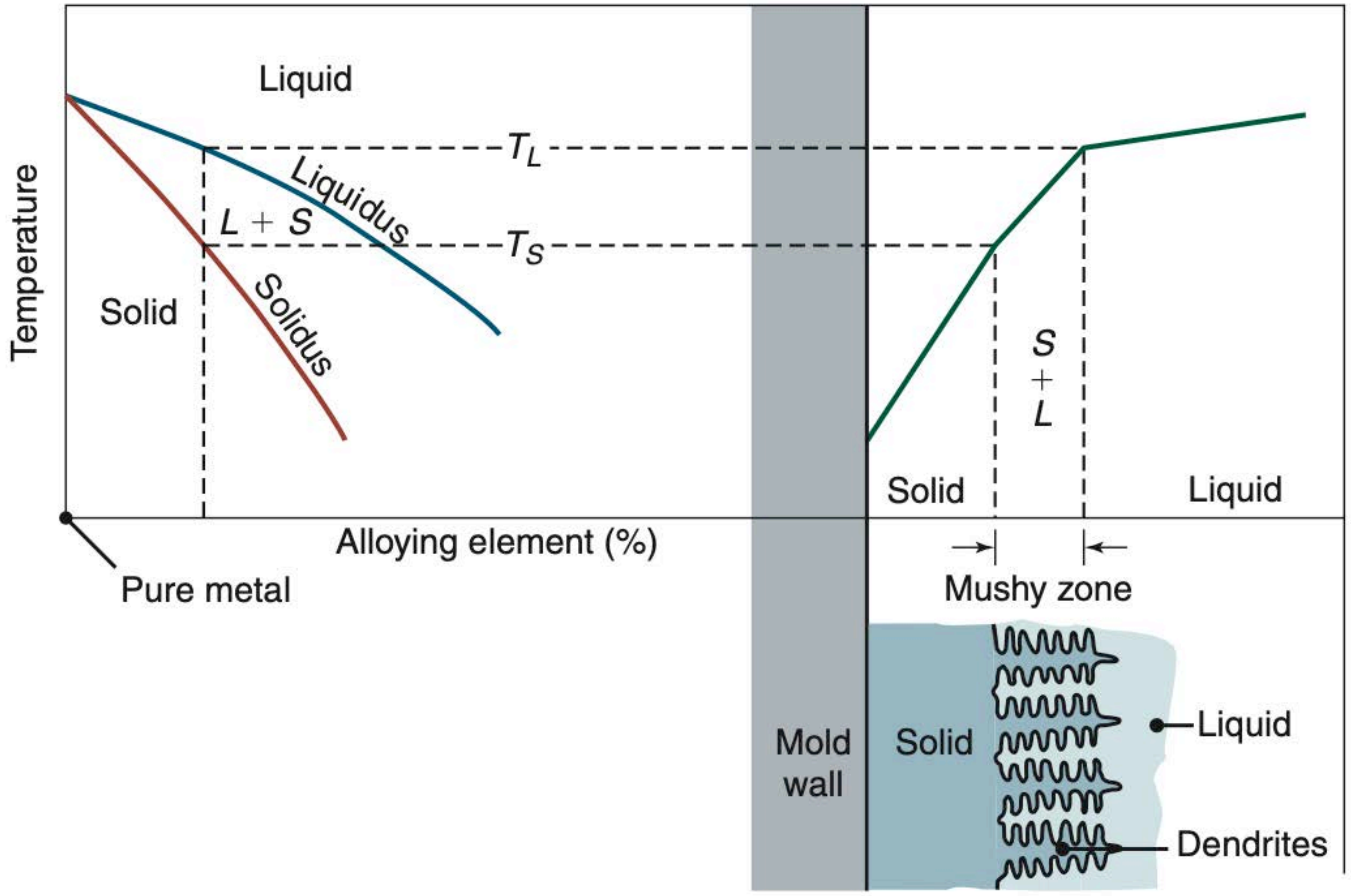
(a)



(b)

phase change

Solidification of a Binary Alloy



Cast Microstructure

Hall-Petch model: smaller grains give higher strength

σ_0 = stress to start dislocation movement
k_y = material hardening constant
d = grain size

$$\sigma_y = \sigma_o + \frac{k_y}{\sqrt{d_{grain}}}$$

- microstructure is affected by cooling rate
- (non-intuitively) thinner cast parts are typically stronger

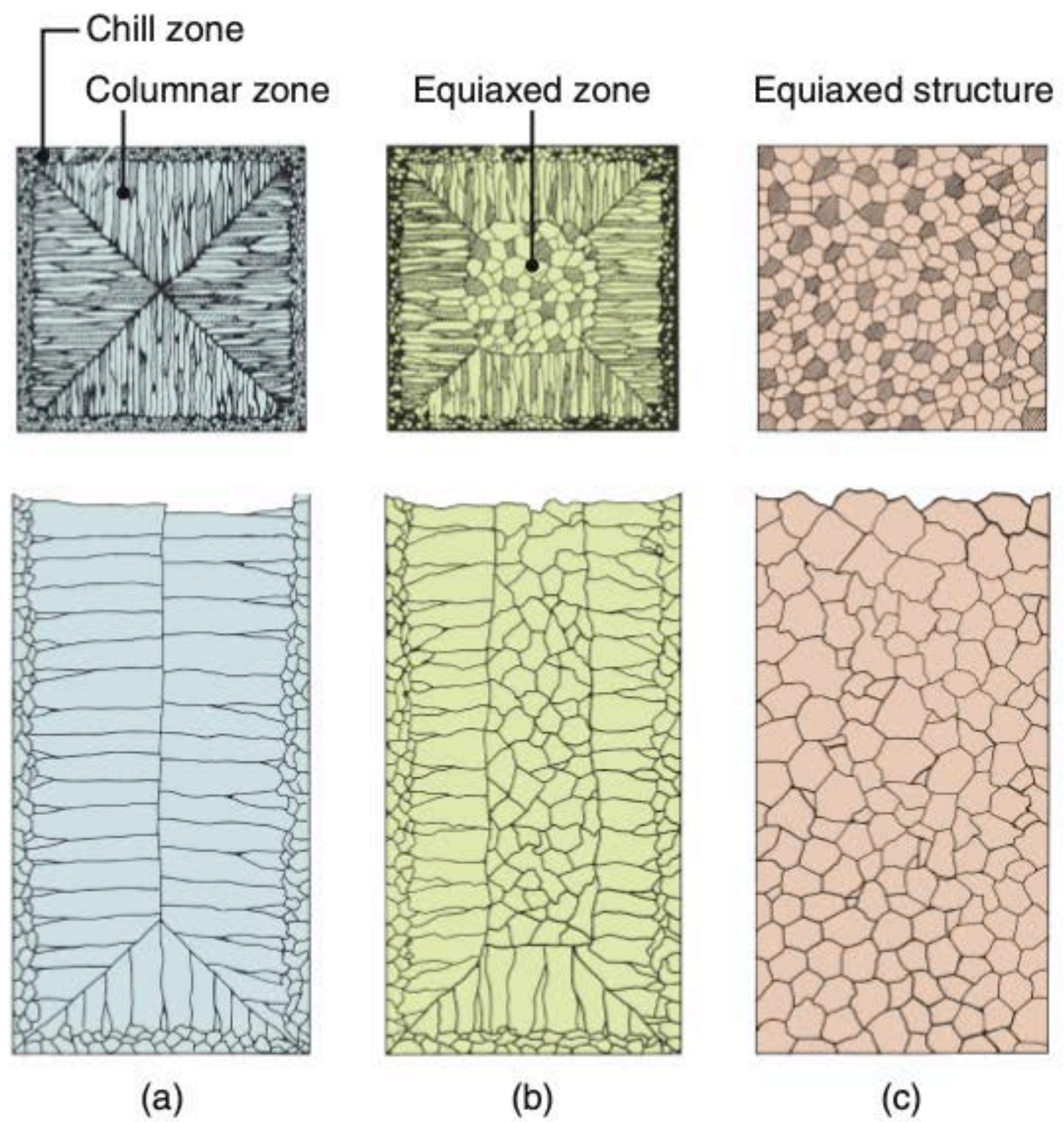
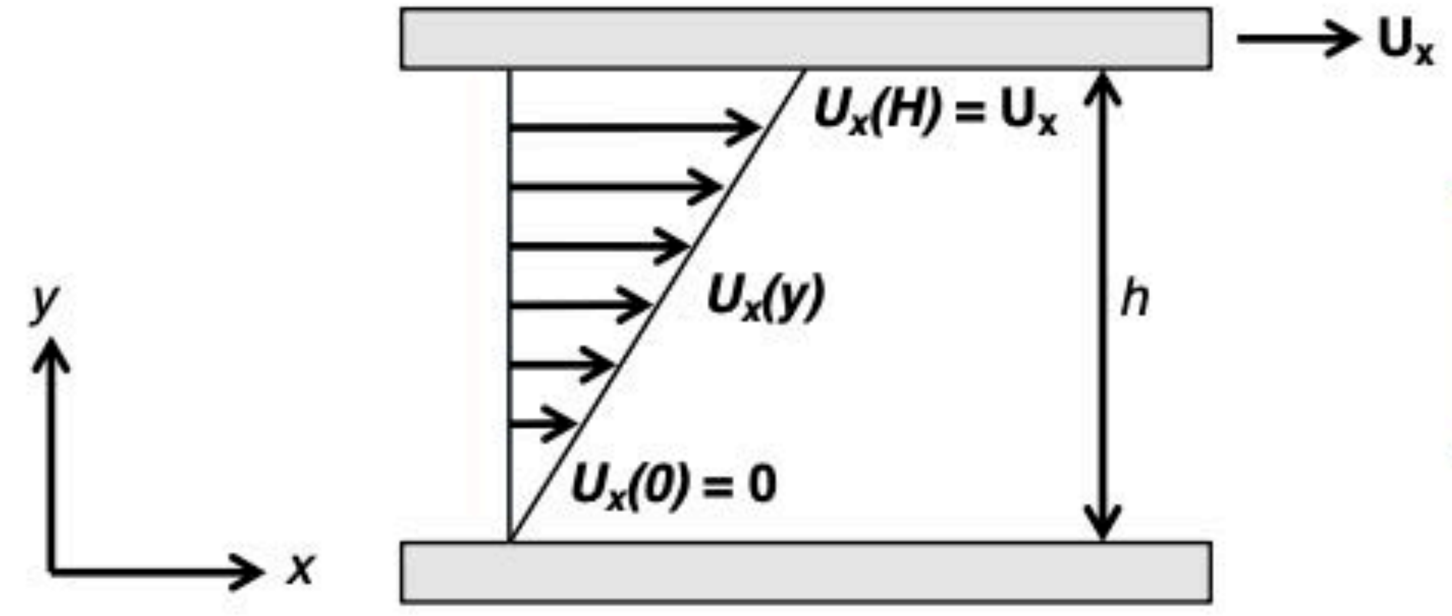


Figure 10.2: Schematic illustration of three cast structures of metals solidified in a square mold: (a) pure metals; (b) solid–solution alloys; and (c) structure obtained by using nucleating agents. *Source:* After G.W. Form, J.F. Wallace, J.L. Walker, and A. Cibula.

Fluid Flow



$$\tau = \mu \frac{\partial U}{\partial y}$$

Material	Dynamic viscosity
Water (room temp)	1×10^{-3} kg/m-s [Pa-s]
Honey	10
Liquid thermoplastic*	**10^{2}-10^{3}**
Molten aluminum (600 C)	3×10^{-3}

surface tension ⬆

Fluid Flow in Sand Casting

susceptible to turbulent flow: molten metal's viscosity is low

$$Re = \frac{\rho v_{run} L_c}{\mu}$$

oxidation, mold erosion, porosity, etc.

vs injection molding?

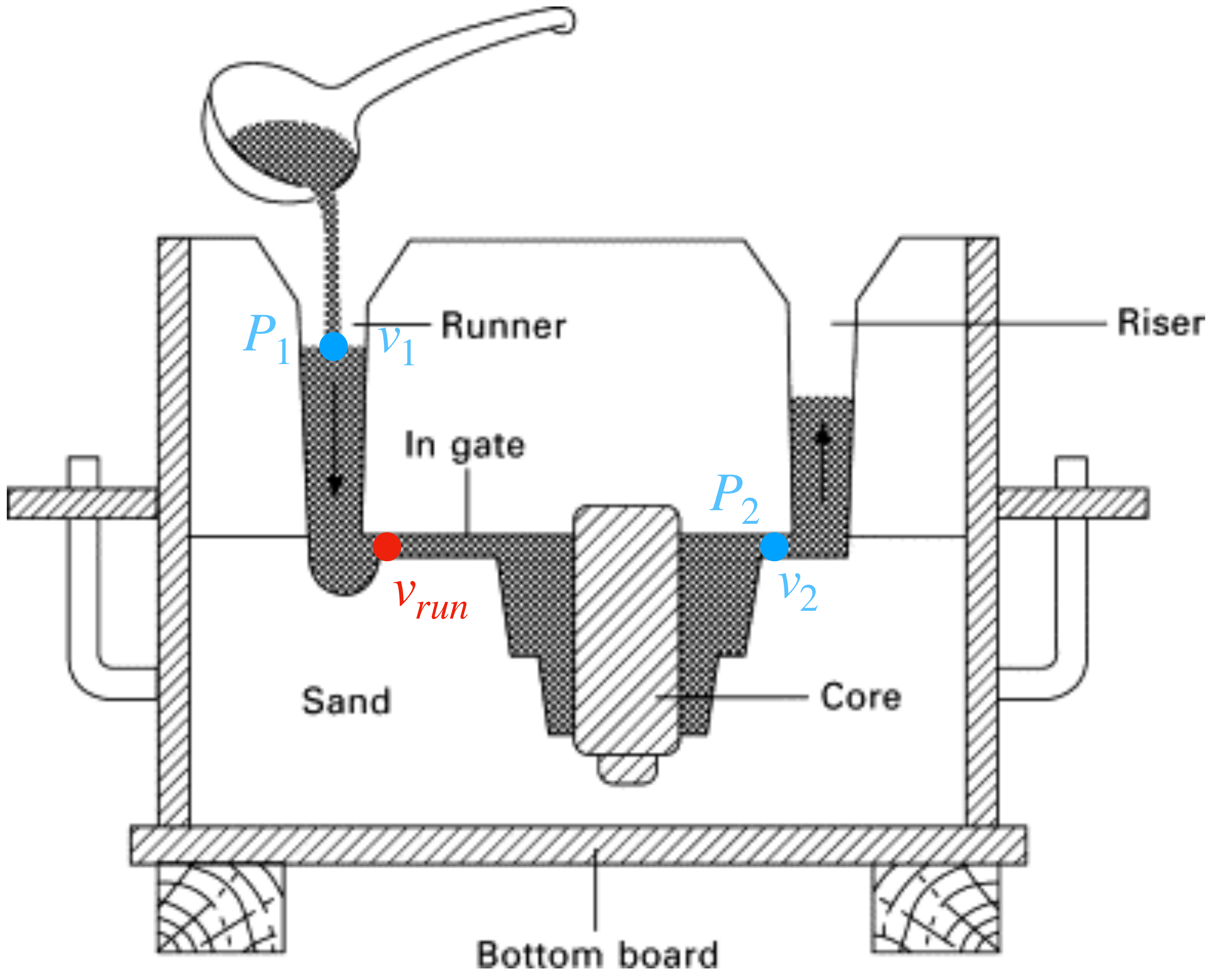
Bernoulli's Principle $P_1 + \frac{\rho v_1^2}{2} + \rho g h_1 - frictional\ losses = P_2 + \frac{\rho v_2^2}{2} + \rho g h_2$

gravity induced flow — reference

during flow: $P_1 + \frac{\rho v_1^2}{2} + \rho g h_1 - frictional\ losses = P_2 + \frac{\rho v_2^2}{2} + \rho g h_2 \rightarrow$ $v_{run} = \sqrt{2gh_1}$

no flow — no flow — reference

after flow: $P_1 + \frac{\rho v_1^2}{2} + \rho g h_1 - frictional\ losses = P_2 + \frac{\rho v_2^2}{2} + \rho g h_2 \rightarrow$ $\Delta P_{static\ pressure} = \rho g h_1$



where does the **clamping force** come from? The weight of the cope:

$$F_{clamp} = \Delta P A_{proj} = m_{cope} g = \rho V_{cope} g$$

Energy Contributions

for metal part + sprue/runners/riser:

$$E_{heat} = mc\Delta T = \rho V c \Delta T$$

$$E_{melt} = mH = \rho V H$$

$$E_{total} = \rho V \Delta T + \rho V H$$

$$\boxed{E_{total} = \rho V (c\Delta T + H)}$$

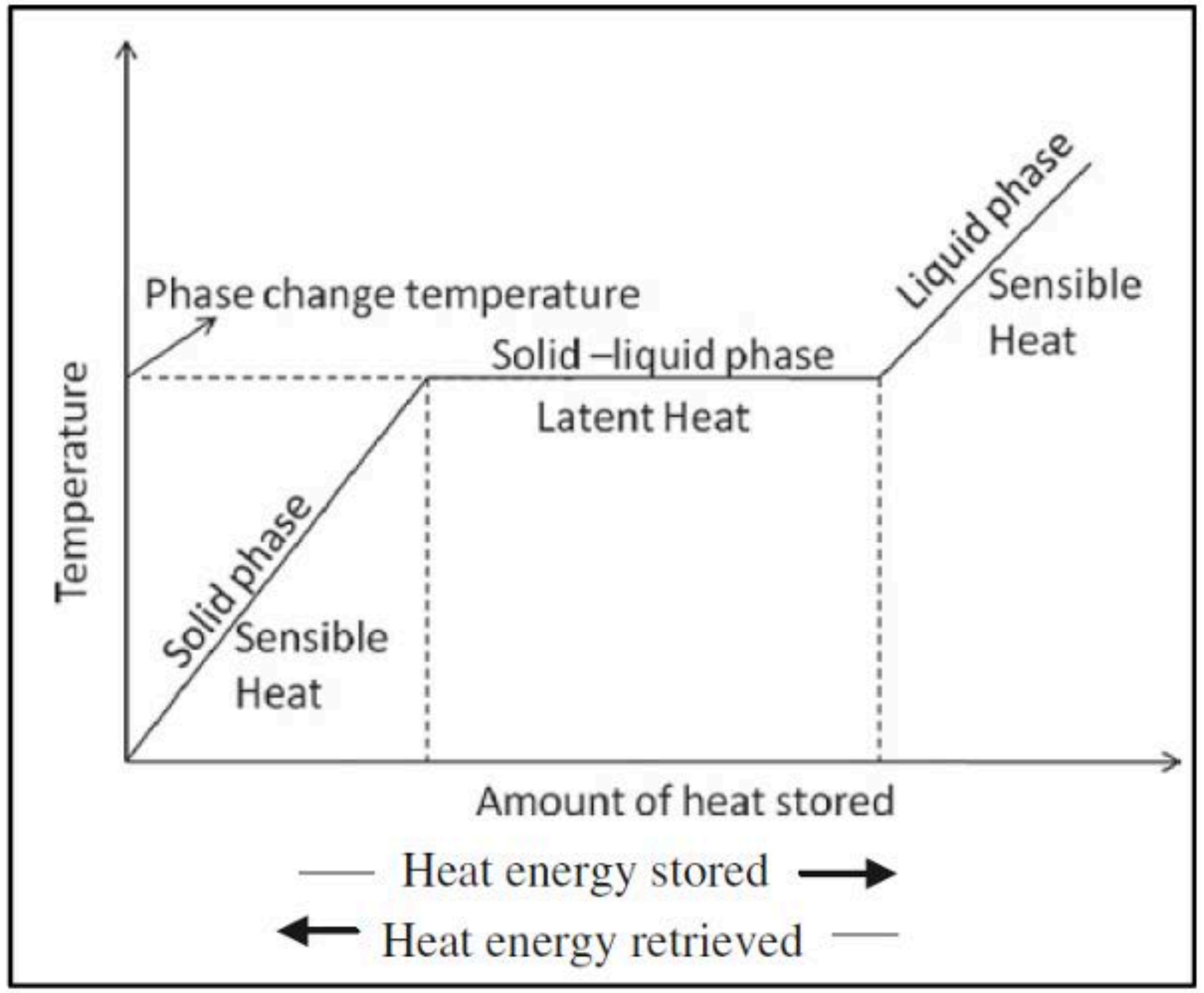
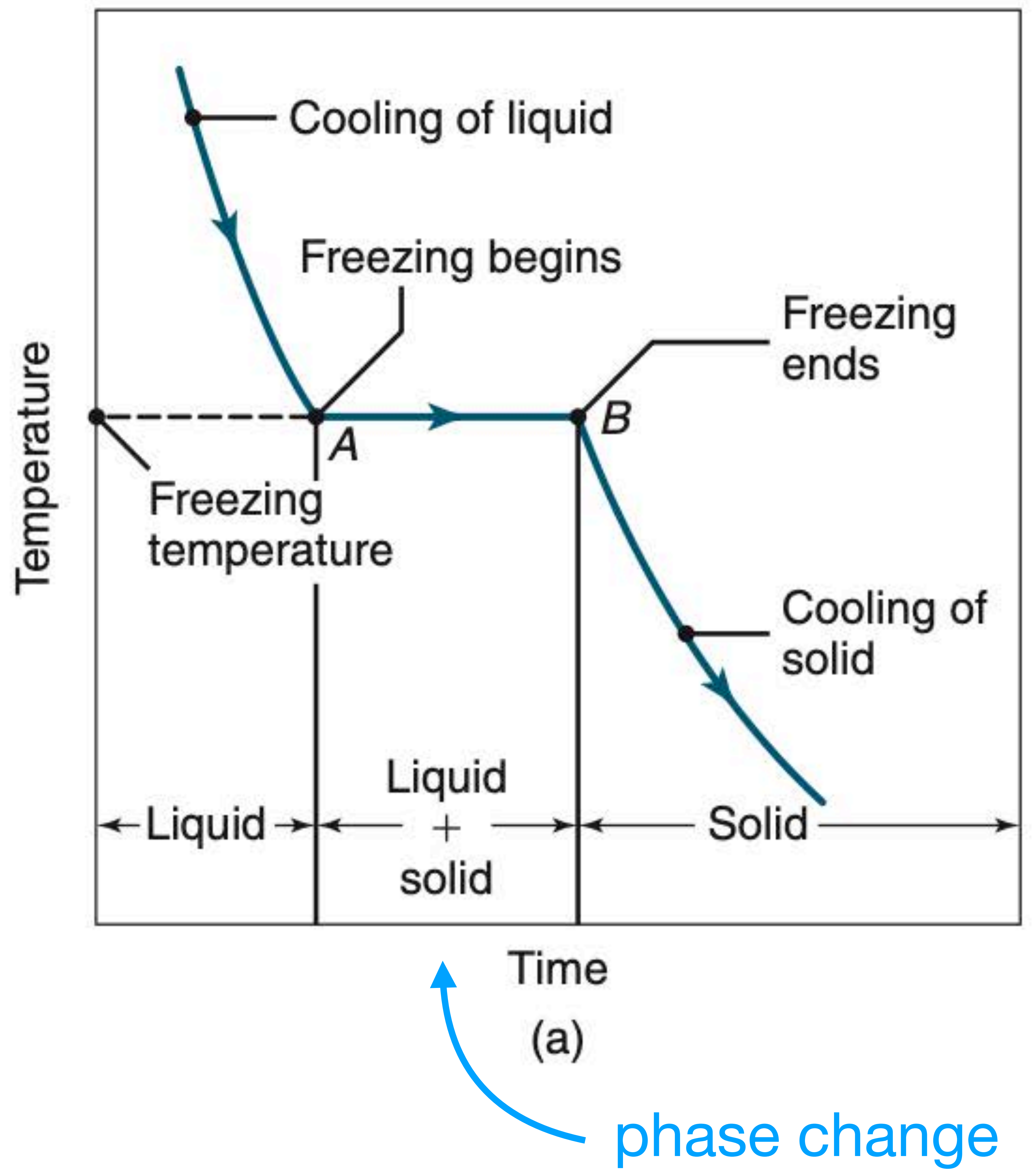


Fig-1: Principle of latent heat storage.

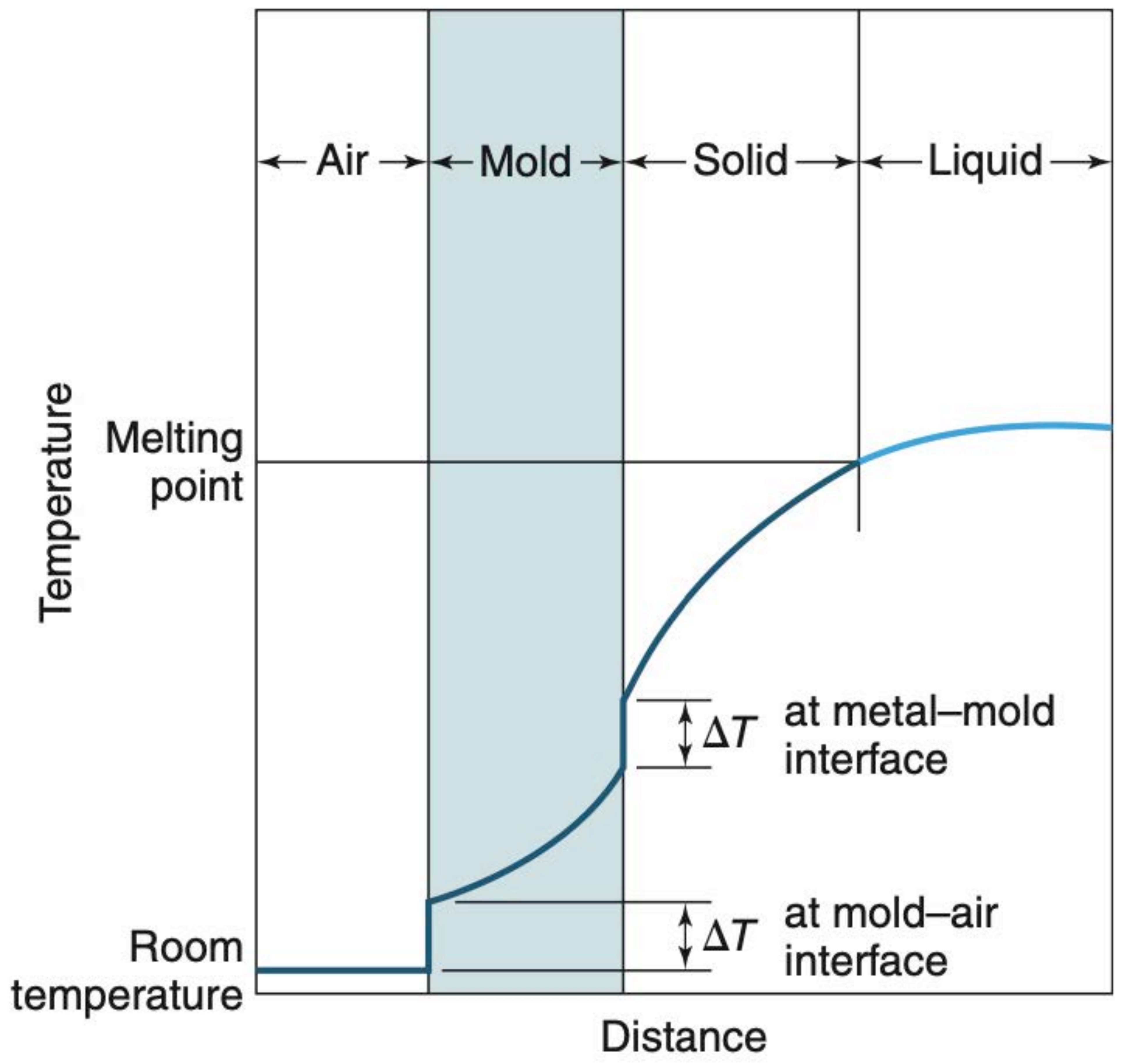
⬆temperature improves fluidity, but ⬆temp also ⬆cost

(requires more energy and takes longer to solidify + cool)

Cooling



Cooling of liquid
Freezing begins
Freezing ends
A
B
Freezing temperature
Temperature
Cooling of solid
Liquid
Liquid + solid
Solid
Time
(a)
phase change

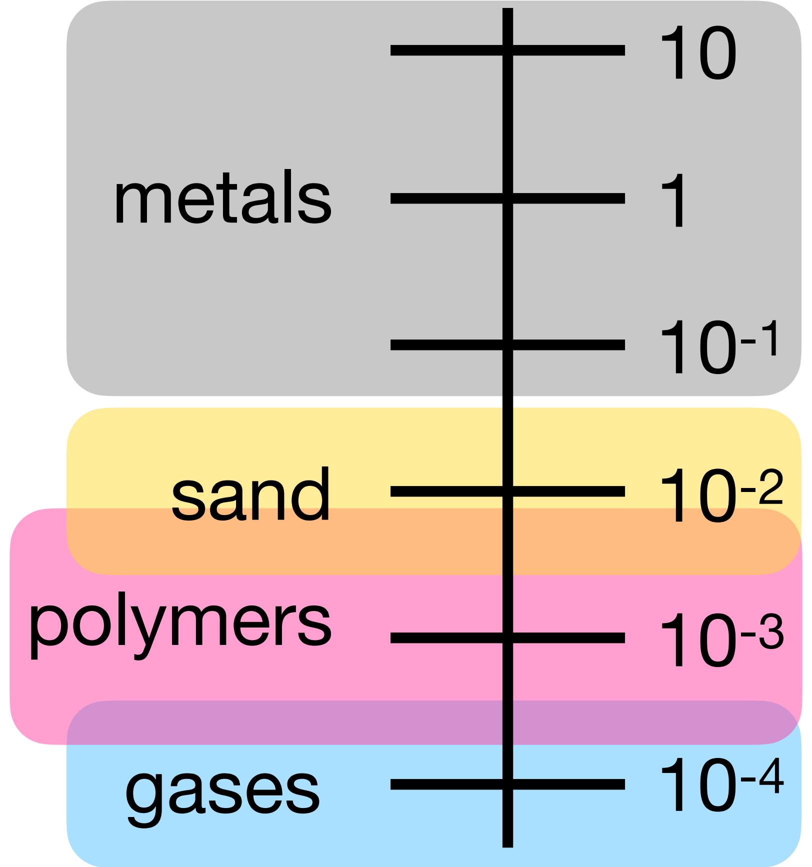


Air
Mold
Solid
Liquid
Temperature
Melting point
ΔT at metal–mold interface
ΔT at mold–air interface
Room temperature
Distance

Cooling

$$\alpha = \frac{k}{\rho c_p}$$

W/mK:
Cu ~ 400, Al ~ 200
Sand ~0.5, PMMA ~0.2

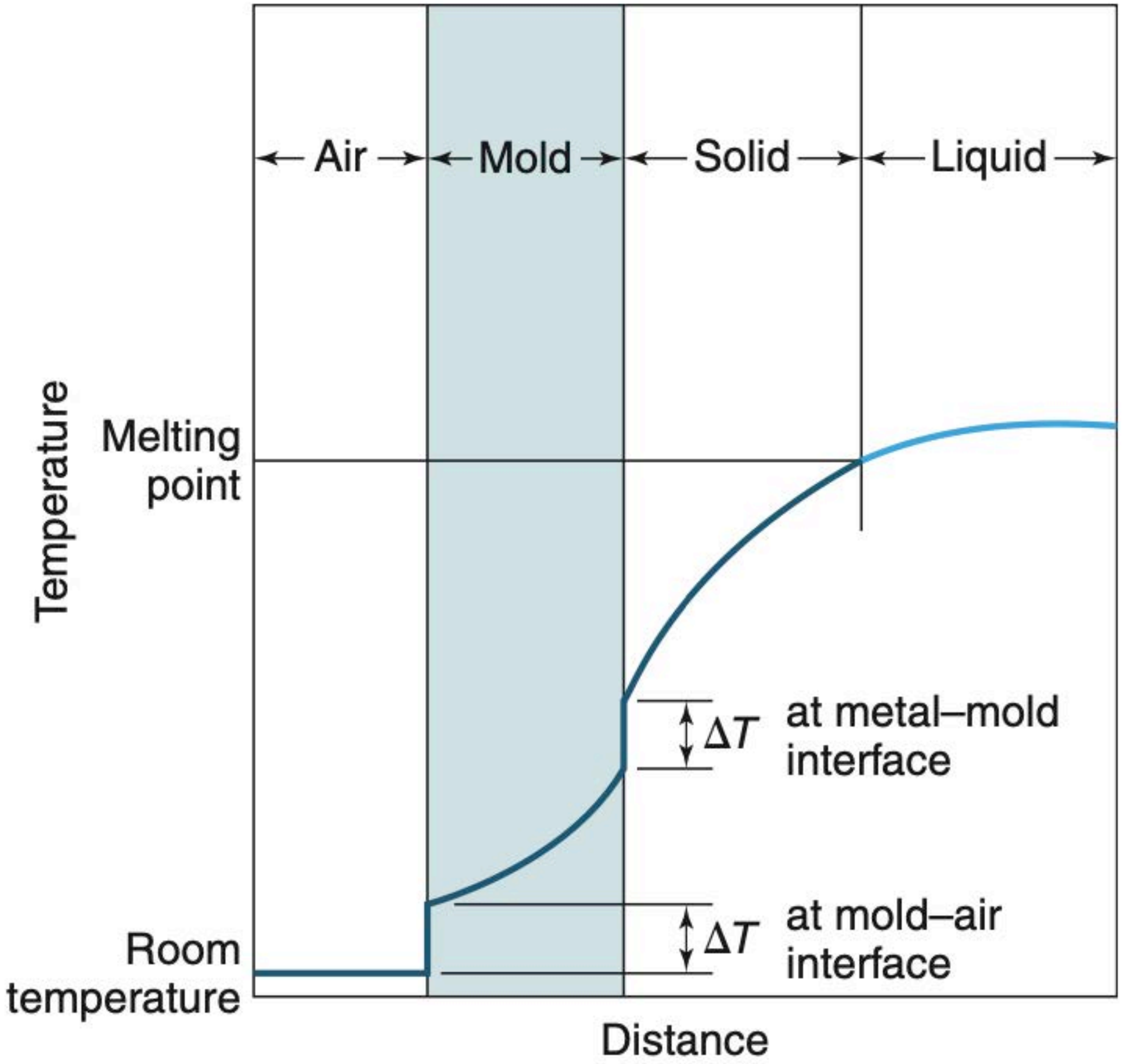


sand casting: $\alpha_{sand} < \alpha_{metal}$

die casting: $\alpha_{tool} = \alpha_{metal}$

injection molding: $\alpha_{tool} > \alpha_{polymer}$

α: thermal diffusivity [m^2/s]
k: thermal conductivity [W/mK]
ρ: density [kg/m^3]
c_p: specific heat capacity [J/kg*K]



Die Casting

- 1-1000 MPa (150 psi to 150 kpsi)

- cycle time: 10s of seconds for tool/toy sized components

- dies: heat-induced cracking/ corrosion + high temperatures: need tool-grade steel or special materials

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- cycle time: 10s of seconds for tool/toy sized components

- dies: heat-induced cracking/corrosion + high temperatures: need tool-grade steel or special materials

Cold Chamber Die Casting

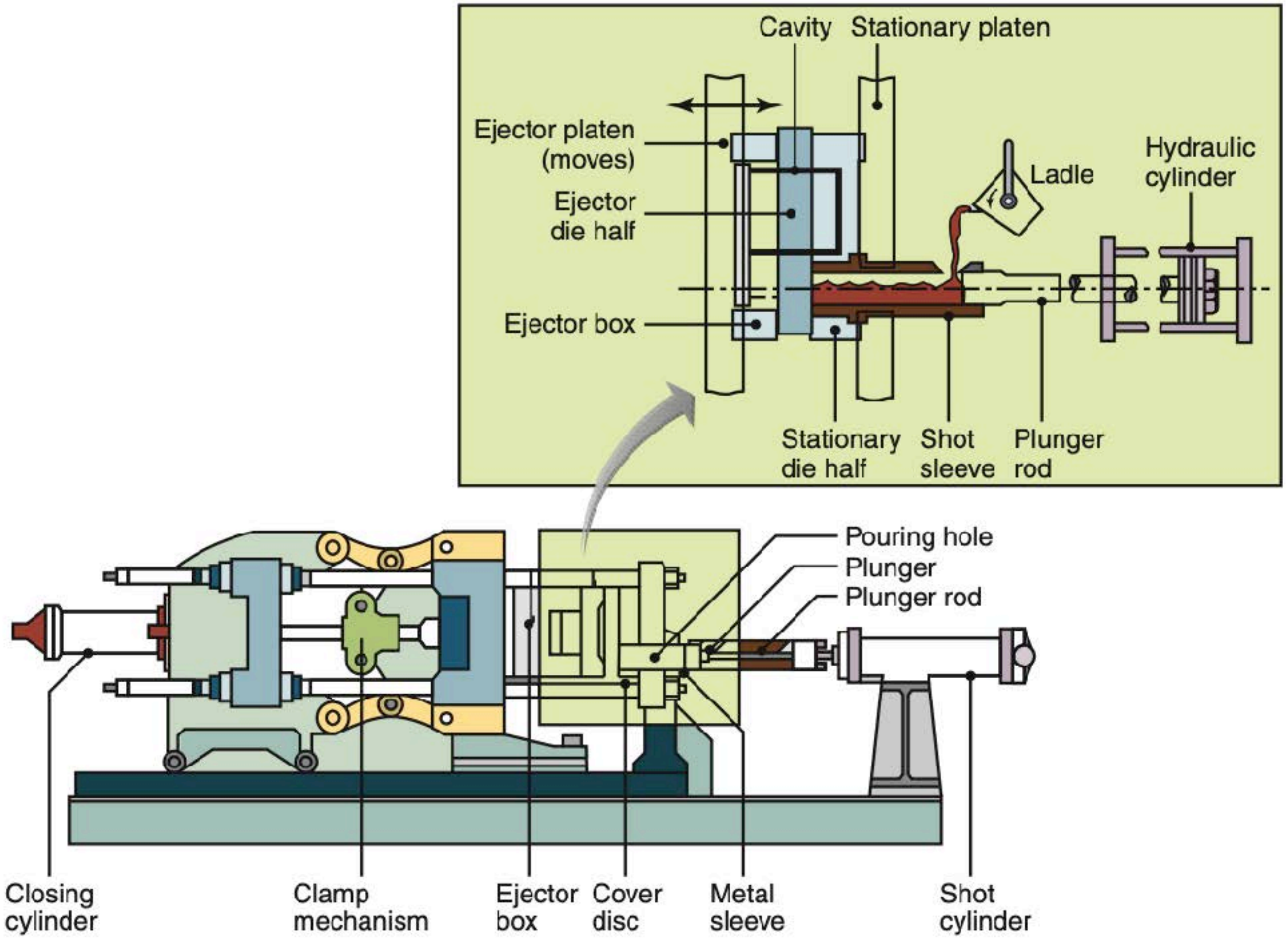


Figure 11.19: Schematic illustration of the cold-chamber die-casting process. These machines are large as compared to the size of the casting, because high forces are required to keep the two halves of the dies closed under pressure.

Hot Chamber Die Casting

Metals: Aluminum, Zinc, Magnesium, and limited Brass.

Size Range: Not normally over 2 feet square. Some foundries capable of larger sizes.

Tolerances:
- Al and Mg ± .002″/in.
- Zinc ± .0015″/in.
- Brass ± .001″/in.
- Add ± .001″ to ± .015″ across parting line depending on size

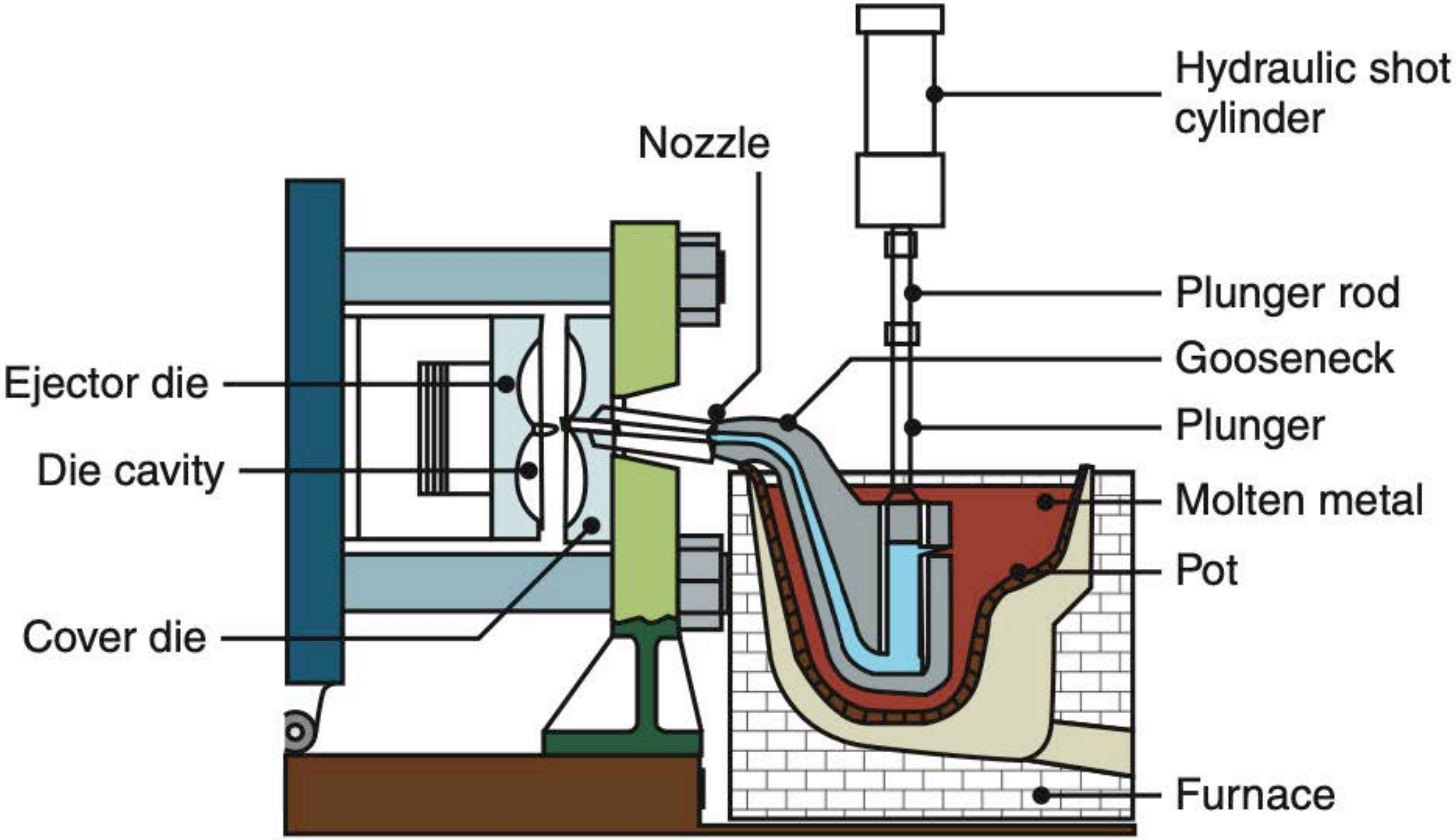
Surface Finish: 32-63RMS

Minimum Draft Requirements:
- Al & Mg: 1° to 3°
- Zinc: 1/2° to 2°
- Brass: 2° to 5°

Normal Minimum Section Thickness:
- Al & Mg: .03″ Small Parts: .06″ Medium Parts
- Zinc: .03″ Small Parts: .045″ Medium Parts
- Brass: .025″ Small Parts: .040″ Medium Parts

Ordering Quantities:
- Usually 2,500 and up.

Normal Lead Time:
- Samples: 12-20 weeks
- Production: ASAP after approval.



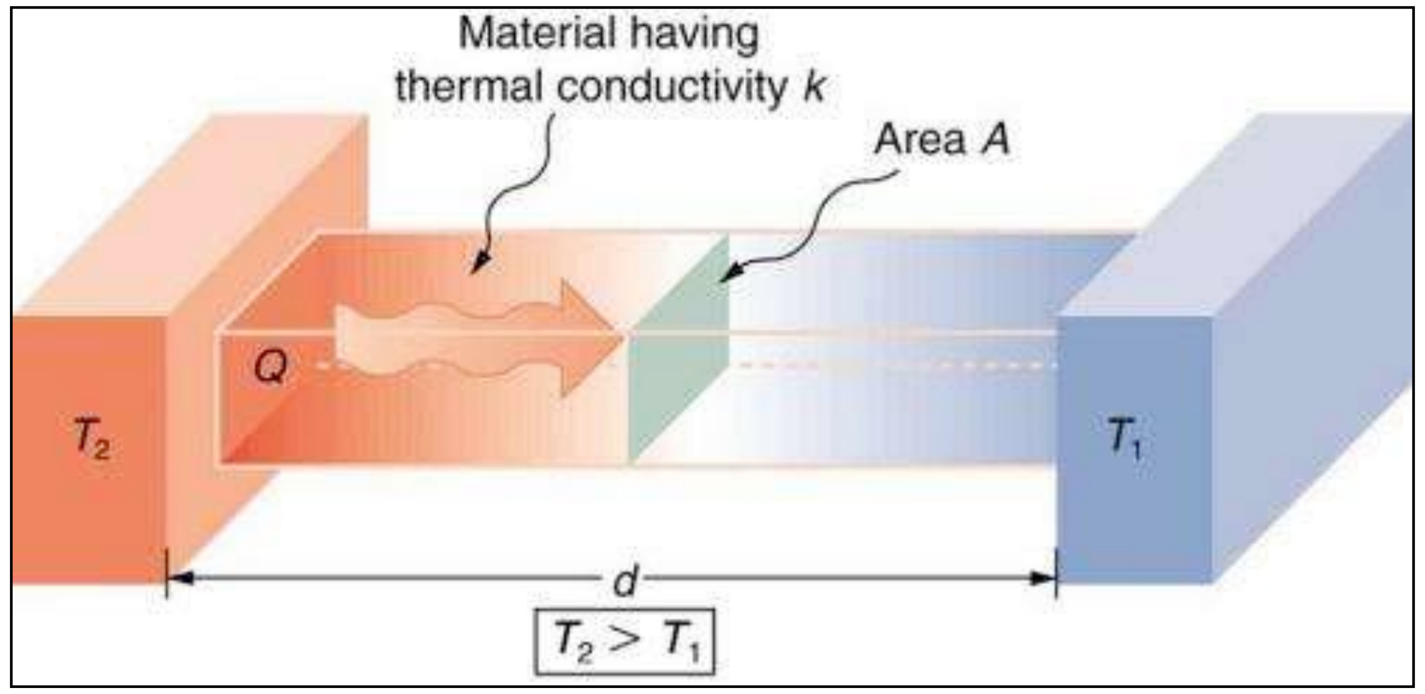
Heat Transfer

$$heat\ capacity,\ \ Q = mc\frac{dT}{dt} \qquad Q = qA$$

Conduction: $$Fourier's\ Law,\ q = -k\frac{dT}{dx}$$

Transient 1-D Conduction: $$\frac{\partial T}{\partial t} = \alpha\frac{\partial^2 T}{\partial x^2}$$

solve to get T(x, t)

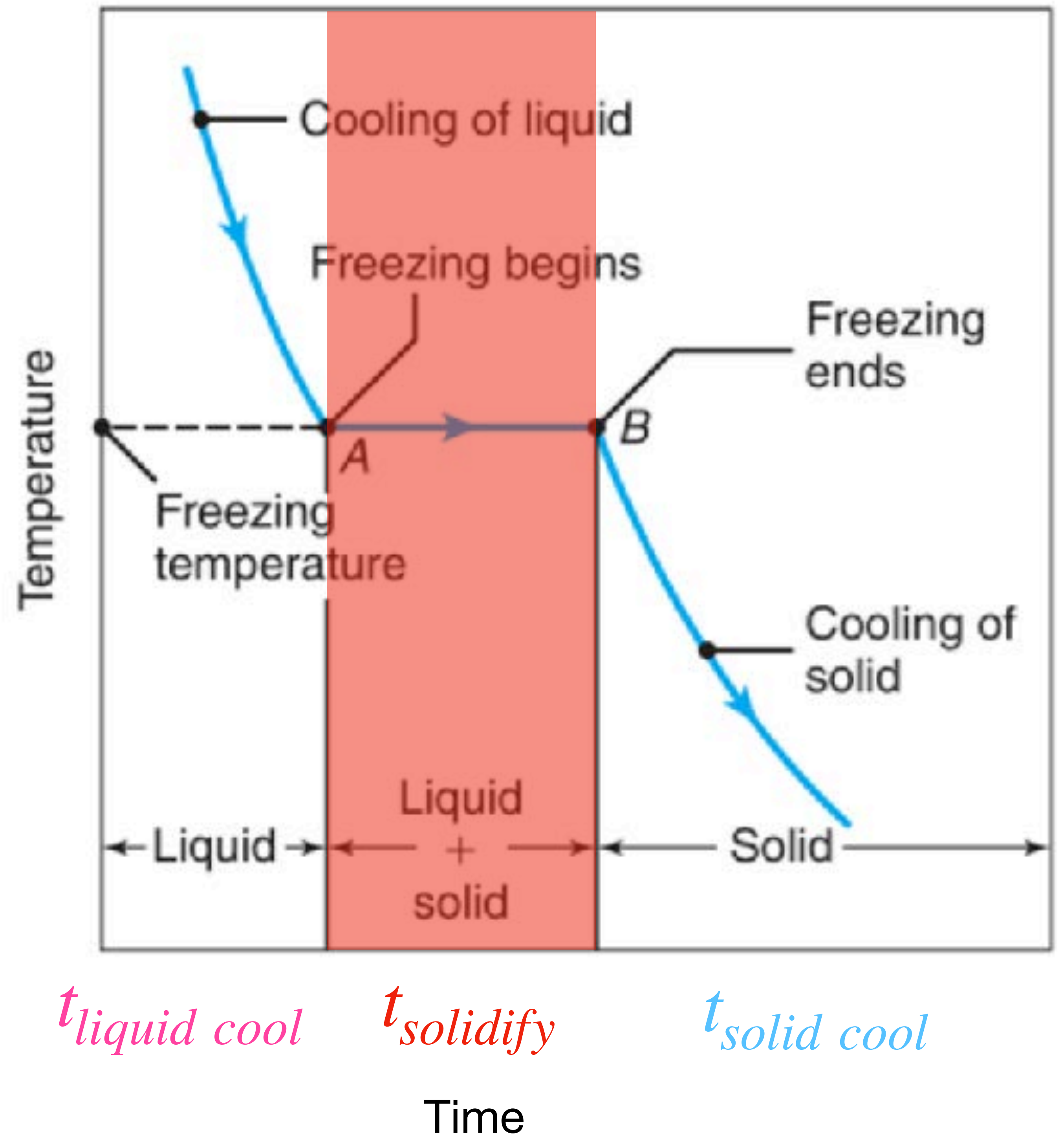


(steady state)

$$\alpha = \frac{k}{\rho c_p}$$

Q: heat transfer rate [J/s] or [W]
q: heat flux [W/m²]
m: mass [kg]
c: specific heat capacity [J/kg*K]
c_p: same as c if incompressible
T: temperature [K]
t: time [s]
α: thermal diffusivity [m²/s]
k: thermal conductivity [W/mK]
ρ: density [kg/m³]

Solidification: Sand Casting

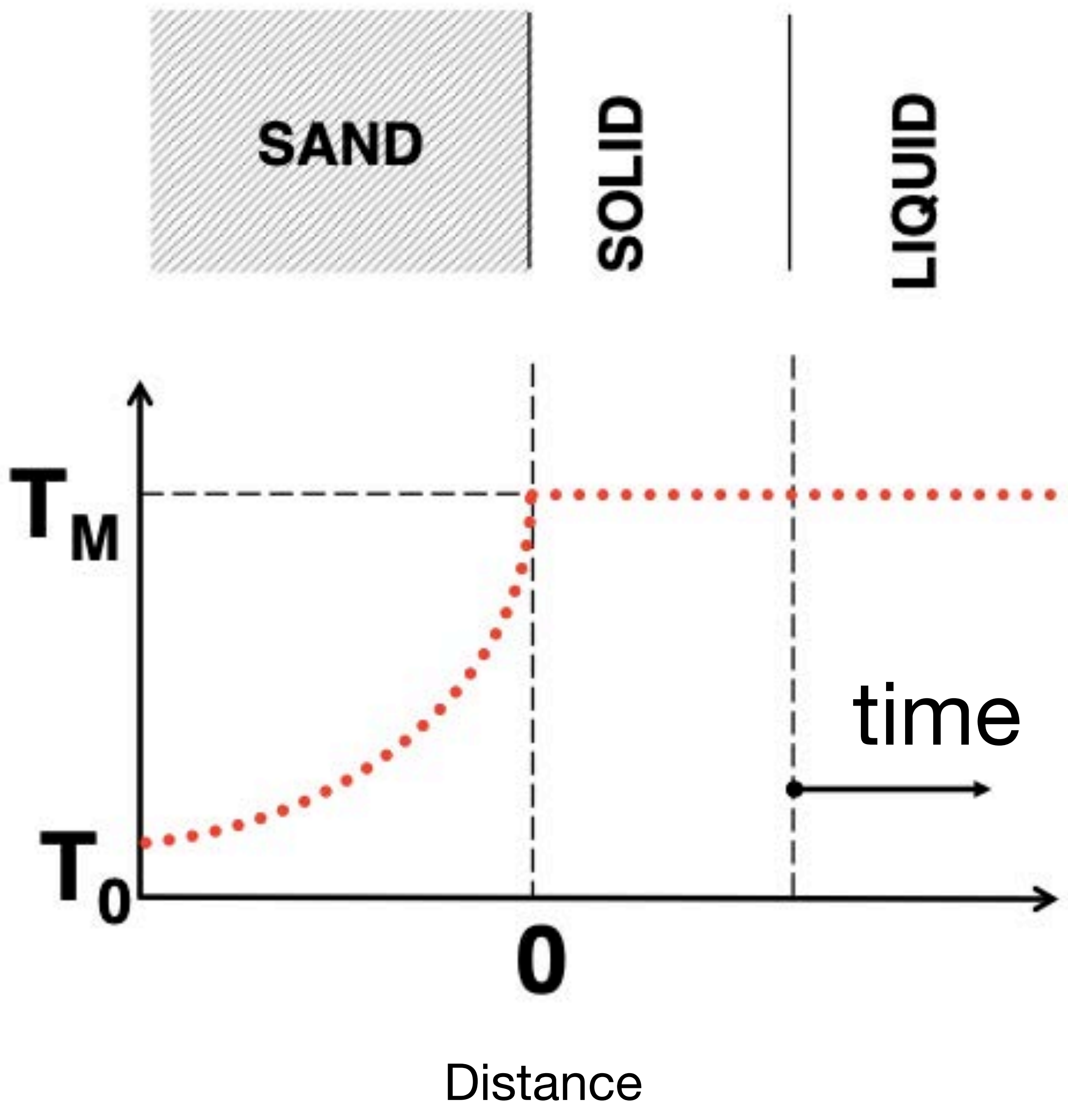


limited by heat transfer through the sand

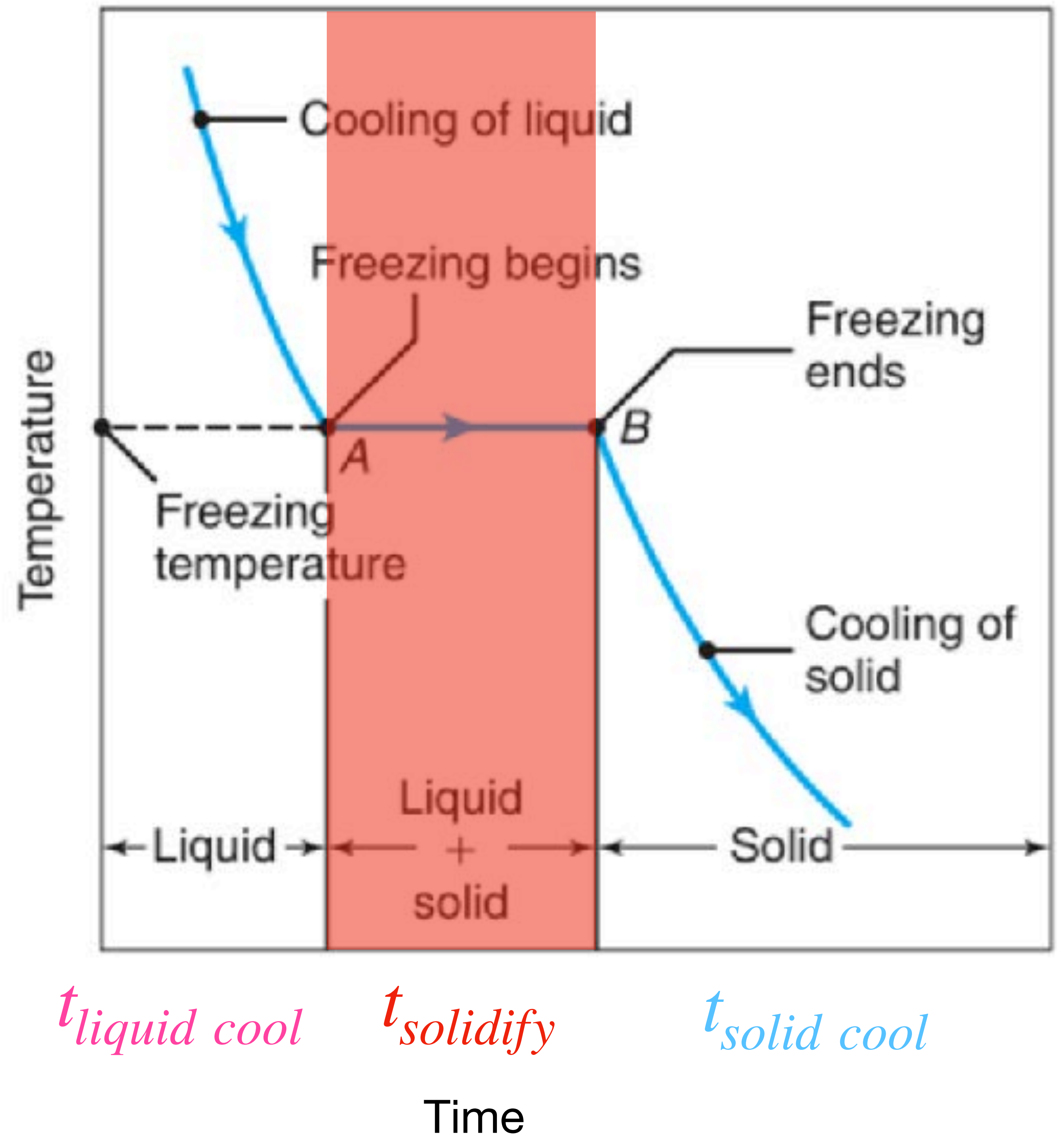
Transient 1-D Heat Transfer: $\frac{\partial T}{\partial t} = \alpha_{sand} \frac{\partial^2 T}{\partial x^2}$

$$t_{solidify} = C \left(\frac{V}{A}\right)^2$$ "Chvorinov's Rule"

C: constant (mold materials, metal properties, temperature dependent)
V: Volume
A: Surface Area (heat transfer)
note: V/A → effective "thickness"



Solidification: Die Casting

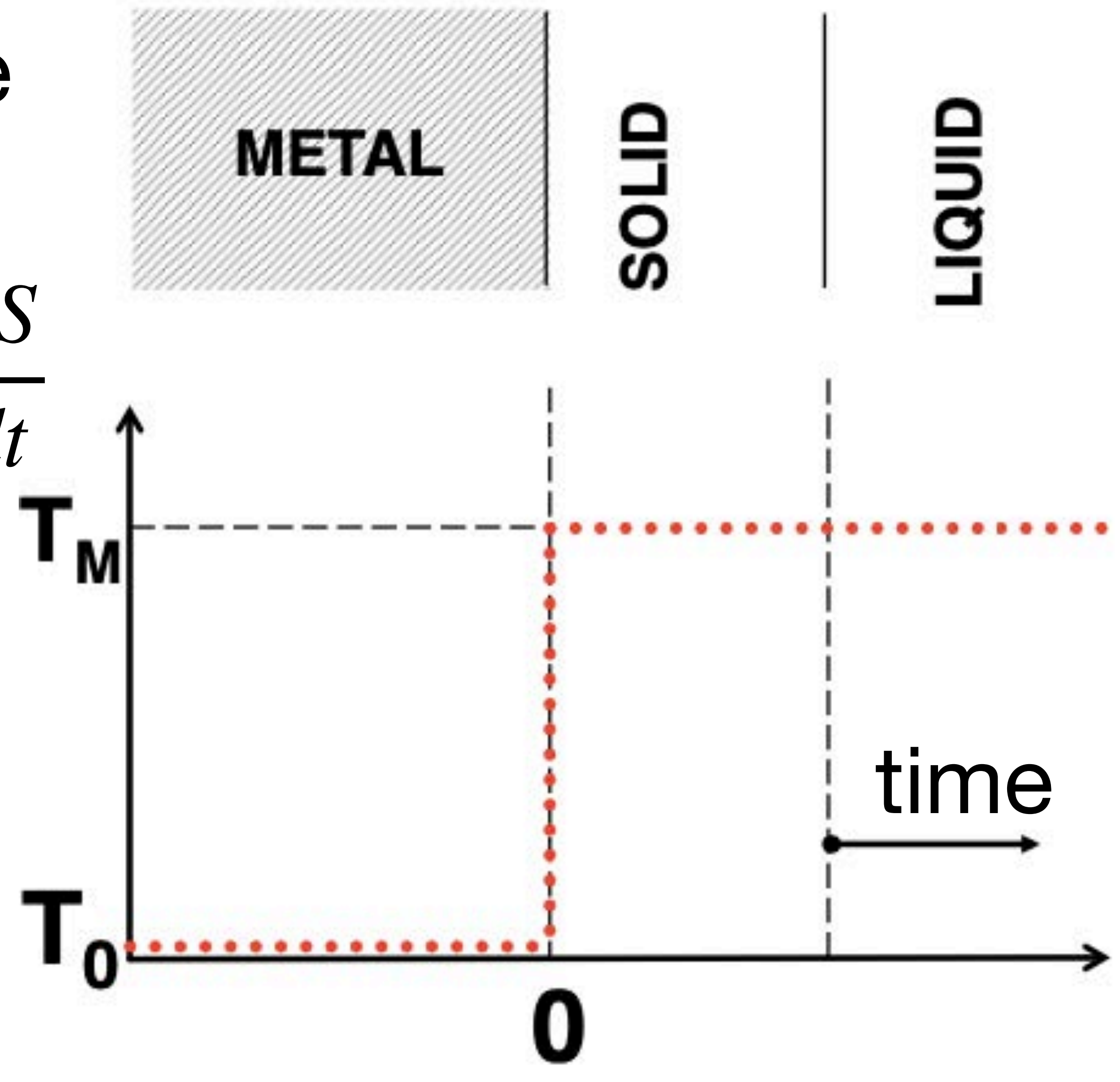


limited by heat transfer at the die-part interface

Transient 1-D Heat Transfer: $h(T_{melt} - T_0) = \rho_s H \frac{dS}{dt}$

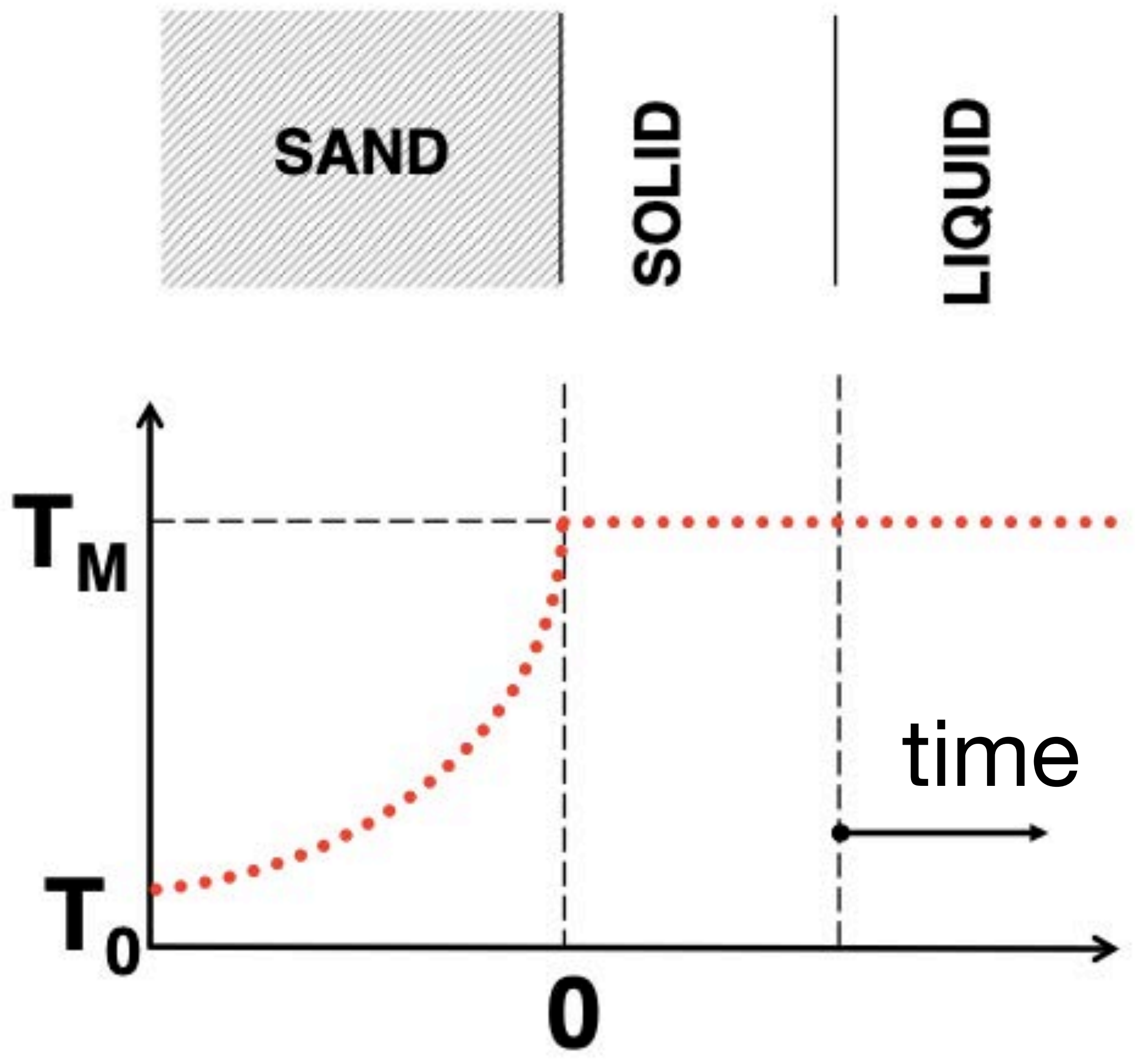
$$t_{solidify} = C\left(\frac{V}{A}\right)^1$$ solidification time

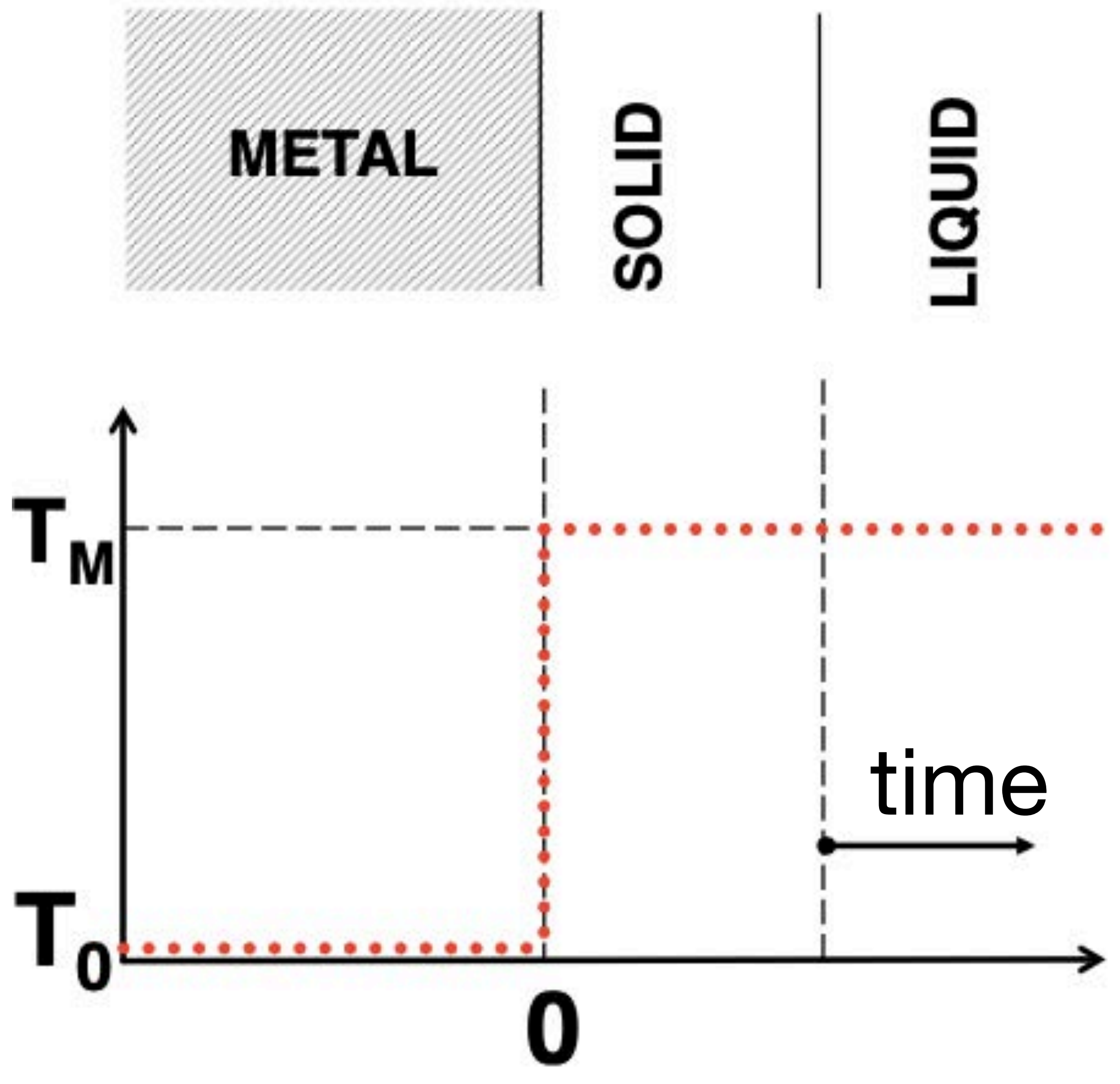
C: constant (mold materials, metal properties, temperature dependent)
V: Volume
A: Surface Area (heat transfer)
note: V/A → effective "thickness"



(assume mold temp is constant)

Solidification: Die Casting

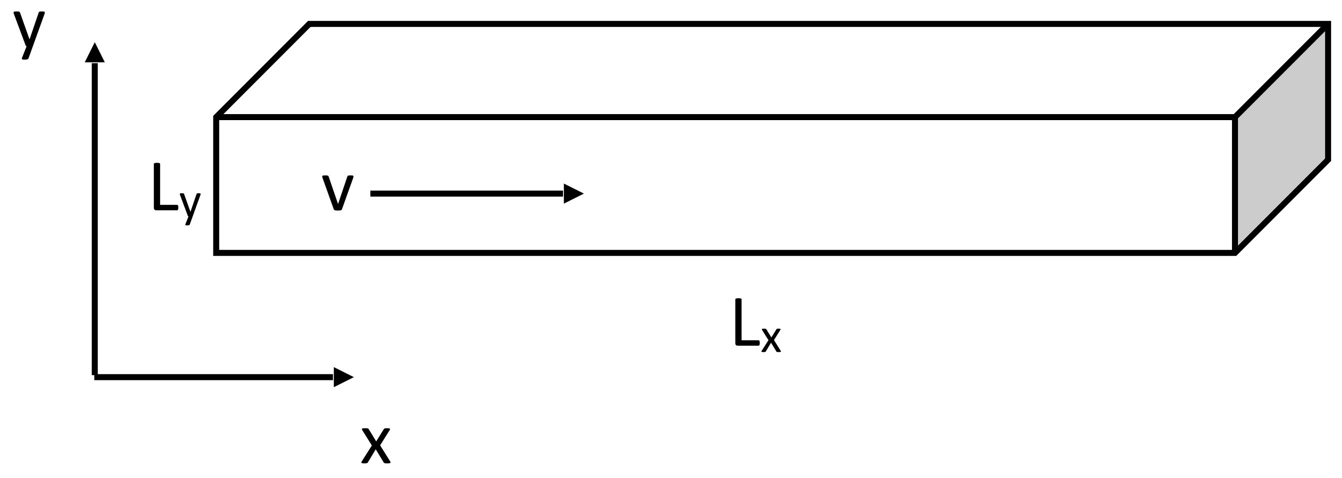


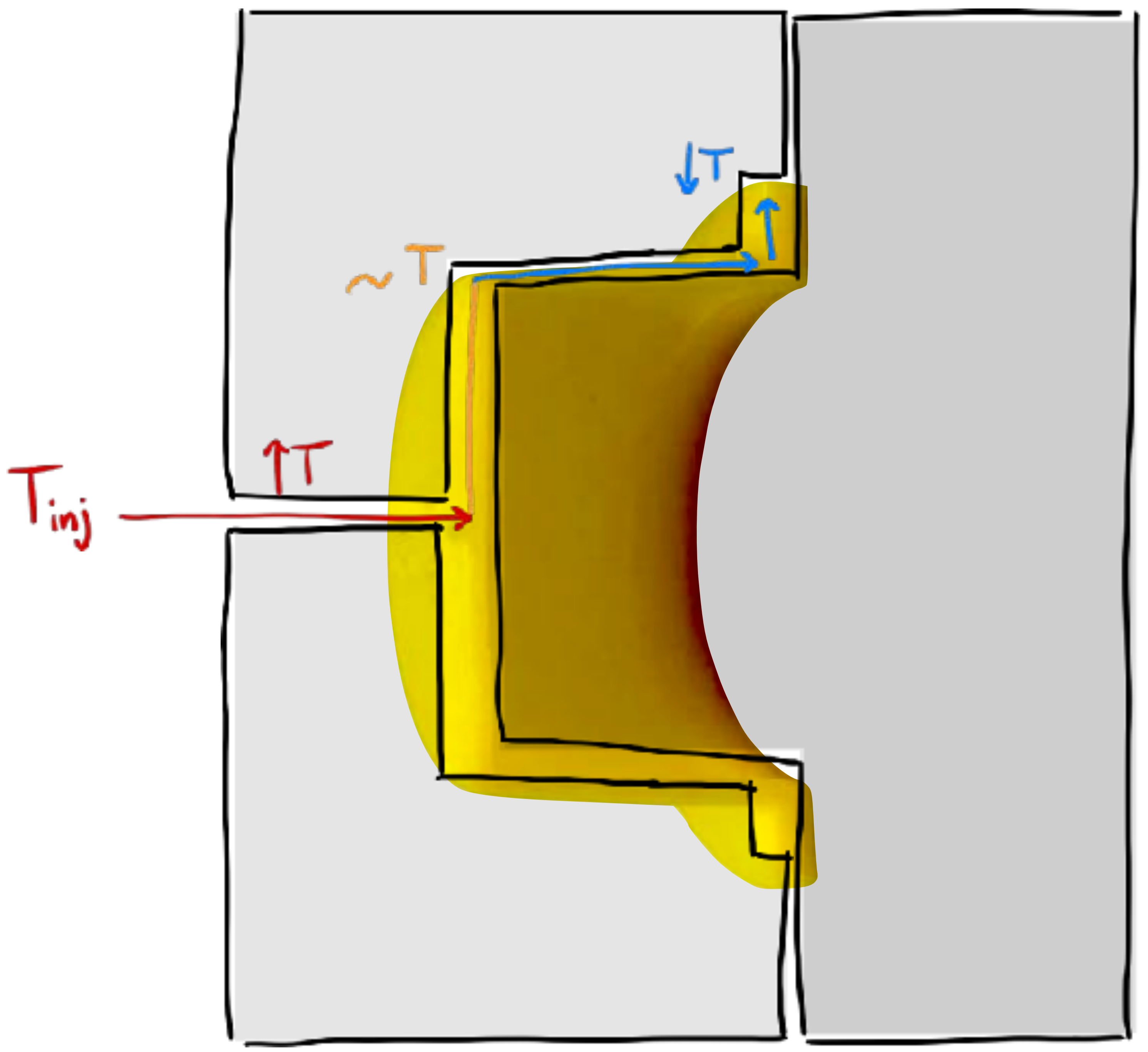


$$t_{solidify} = C\left(\frac{V}{A}\right)^2$$ sand casting

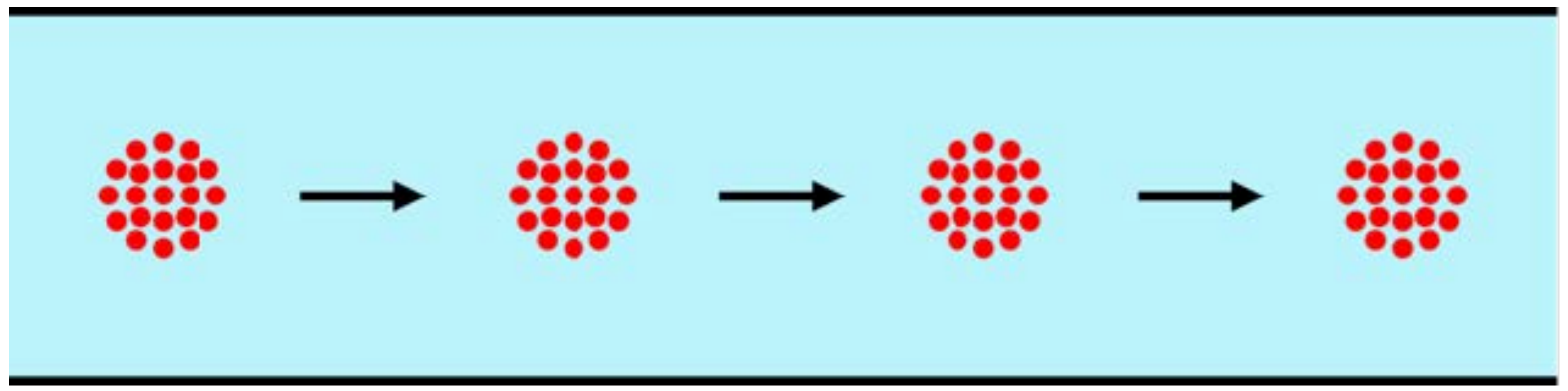
$$t_{solidify} = C\left(\frac{V}{A}\right)^1$$ die casting

Fluid Flow vs Heat Transfer

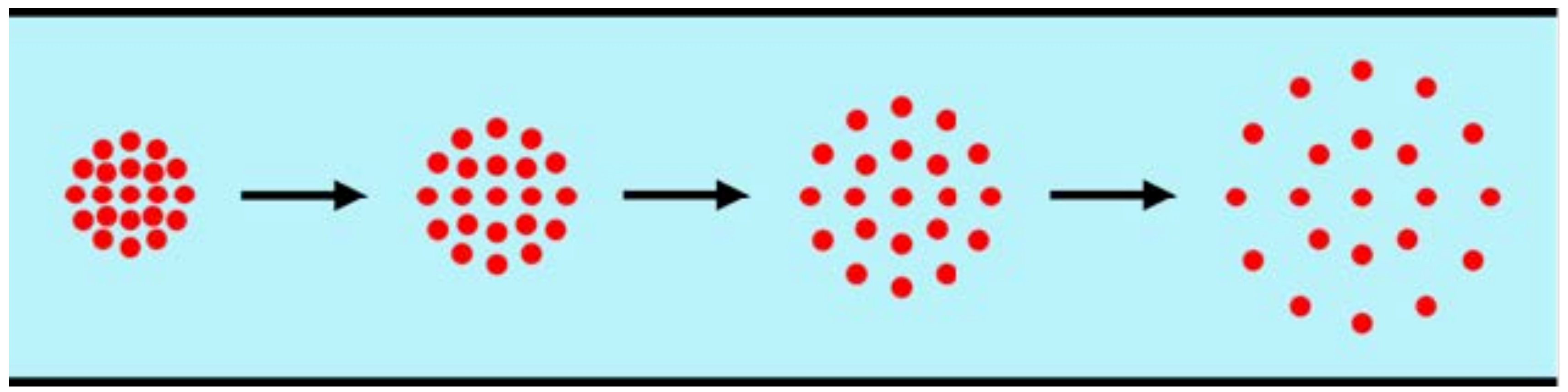




fluid flow dominates



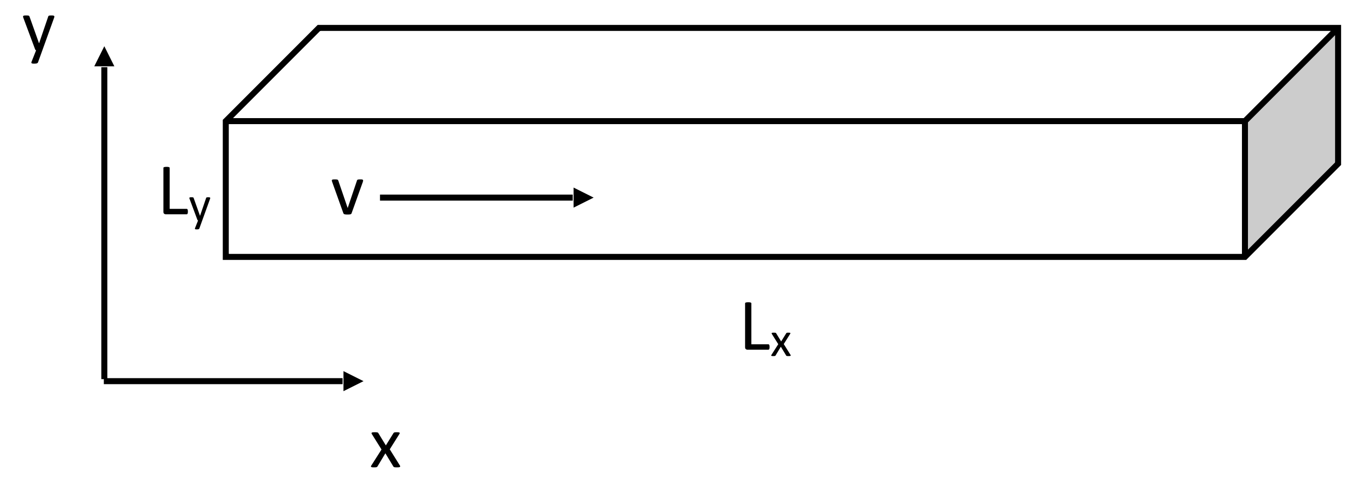
evenly matched



heat transfer dominates

Fluid Flow vs Heat Transfer

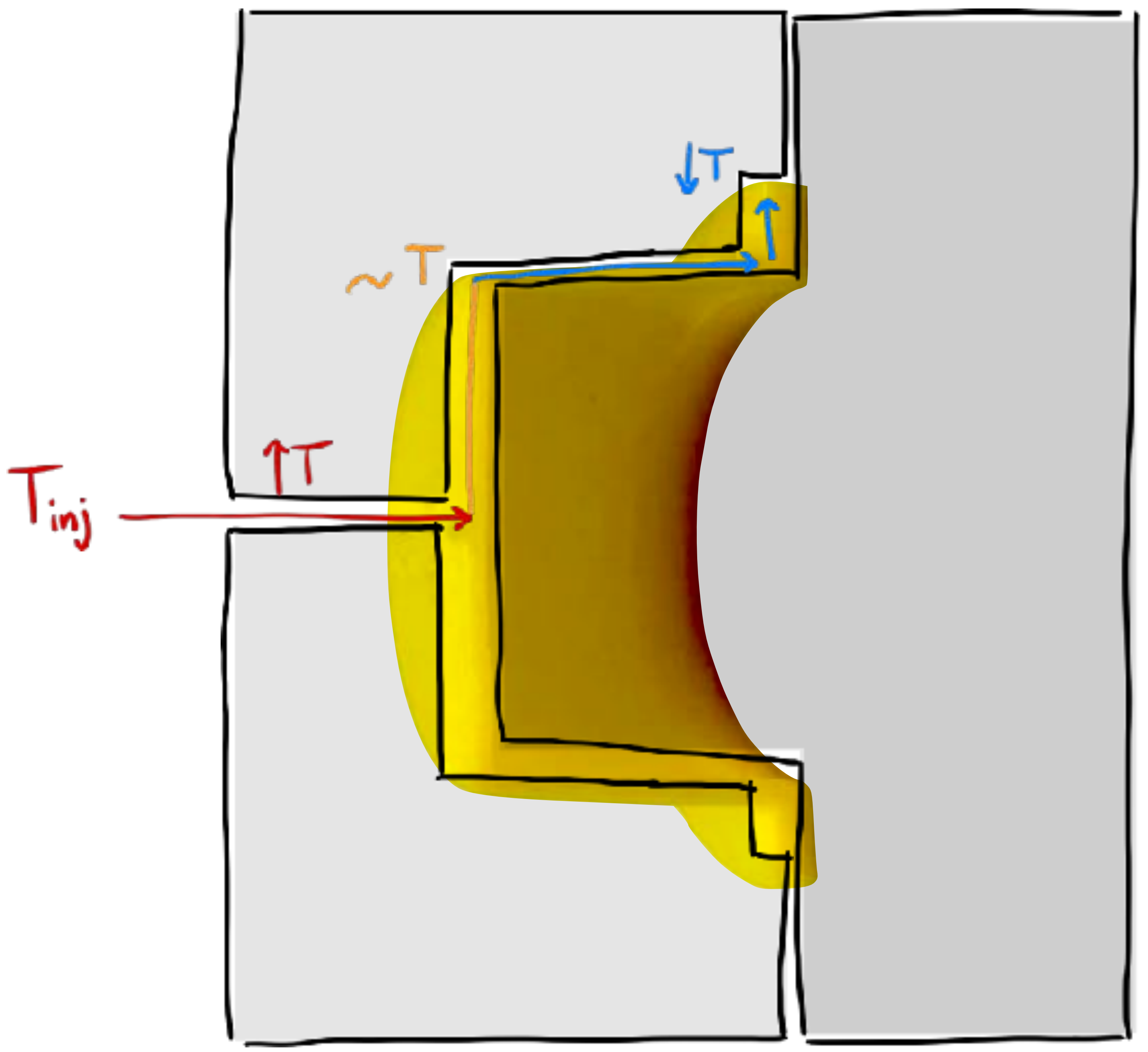
"rate / length"



$$flow\ rate = \frac{1}{t} = \frac{v}{L_{c-flow}}$$

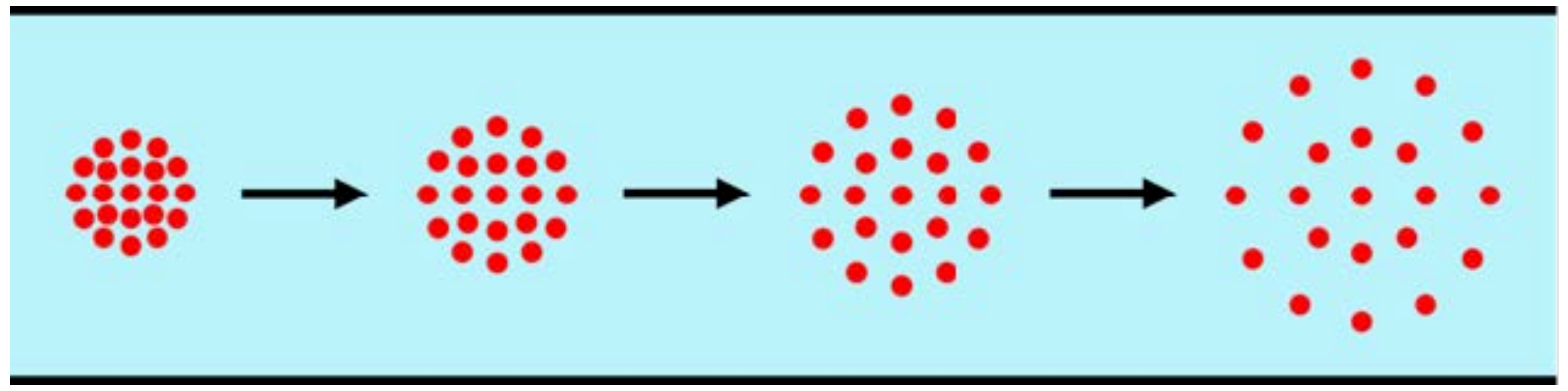
how many length scales does mass travel per unit time?

$$L_c \rightarrow \frac{Vol}{SA}$$



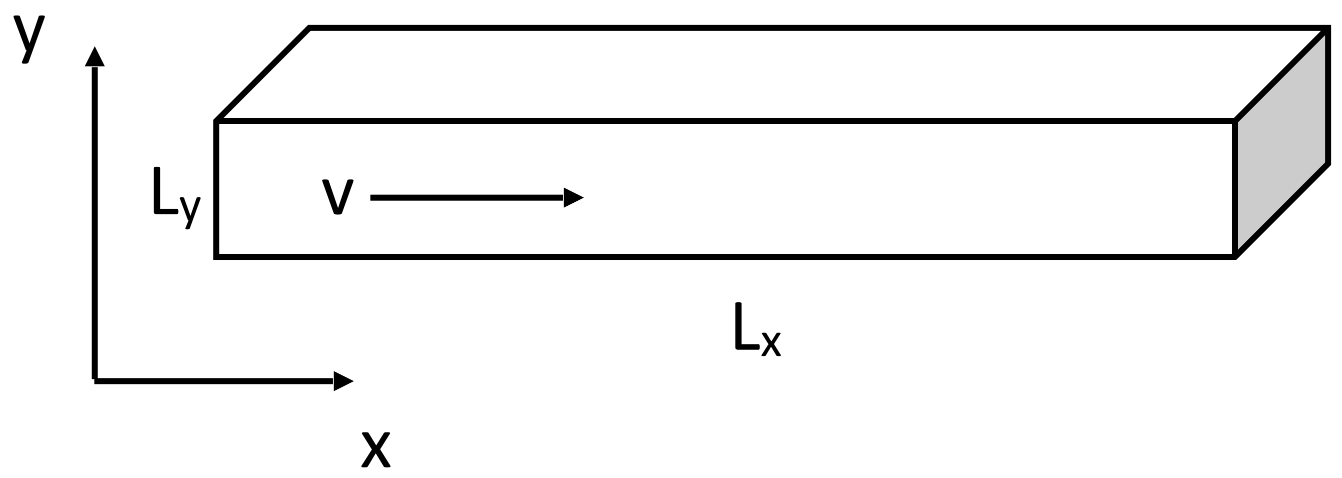
$$heat\ transfer\ rate = \frac{1}{t} = \frac{\alpha}{(L_{c-heat})^2}$$

how many length scales does heat diffuse per unit time?



$$\frac{flow\ rate}{heat\ transfer\ rate} = \frac{vL_{c-heat}^2}{\alpha L_{c-flow}} = \left(\frac{vL_{c-heat}}{\alpha}\right)\left(\frac{L_{c-heat}}{L_{c-flow}}\right)$$

Fluid Flow vs Heat Transfer



$$\frac{flow\ rate}{heat\ transfer\ rate} = \frac{vL_y^2}{4\alpha L_x} = \left(\frac{1}{4}\right)\left(\frac{vL_y}{\alpha}\right)\left(\frac{L_y}{L_x}\right)$$

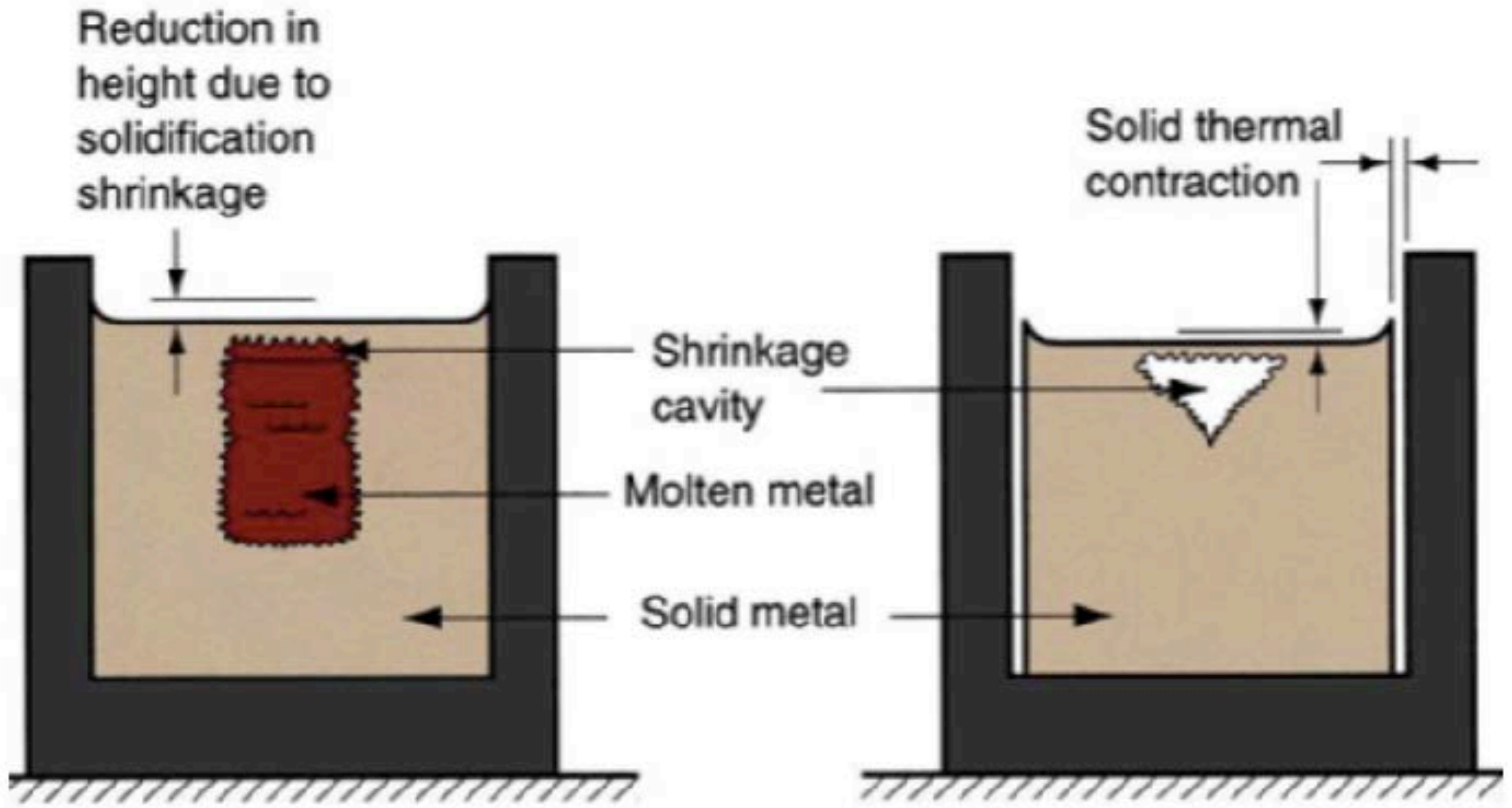
Injection Molding

$$\frac{flow\ rate}{heat\ transfer\ rate} = \left(\frac{1}{4}\right)\left(\frac{vL_y}{\alpha_{polymer}}\right)\left(\frac{L_y}{L_x}\right) = \left(\frac{1}{4}\right)\left(\frac{10\frac{cm}{s}0.1cm}{10^{-3}\frac{cm^2}{s}}\right)\left(\frac{0.1cm}{10cm}\right) = 2.5$$

Die Casting

$$\frac{flow\ rate}{heat\ transfer\ rate} = \left(\frac{1}{4}\right)\left(\frac{vL_y}{\alpha_{metal}}\right)\left(\frac{L_y}{L_x}\right) = \left(\frac{1}{4}\right)\left(\frac{10\frac{cm}{s}0.1cm}{0.3\frac{cm^2}{s}}\right)\left(\frac{0.1cm}{10cm}\right) = 0.008$$

Defects: Voids



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Phosphor bronze	1.0–1.6
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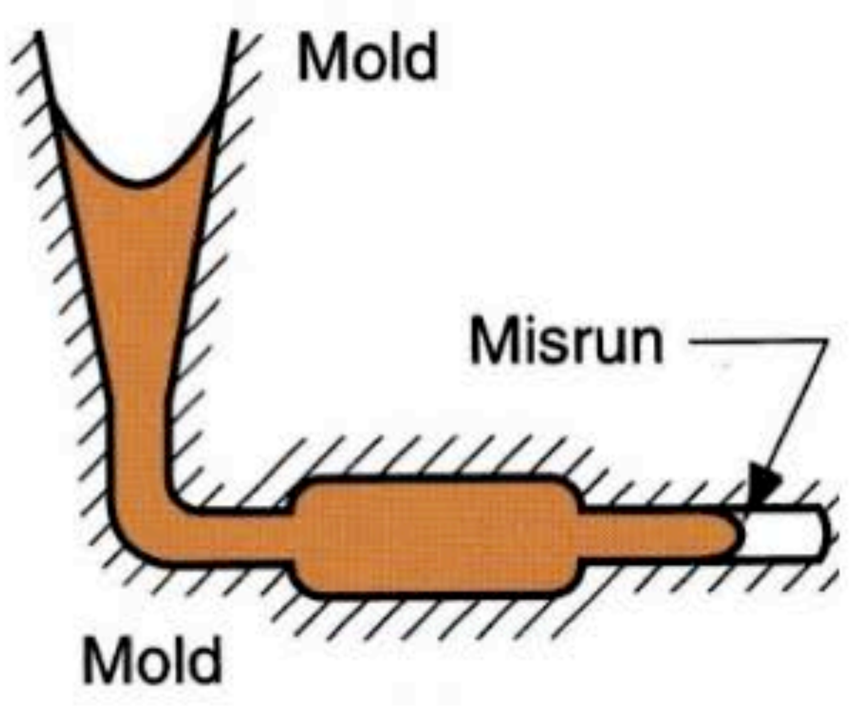
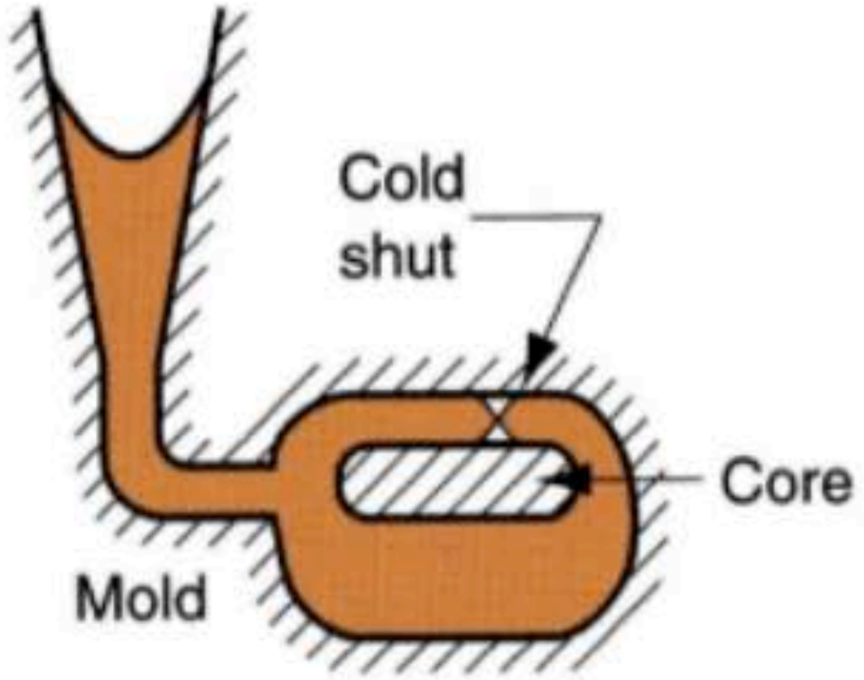
High-manganese steel	2.6

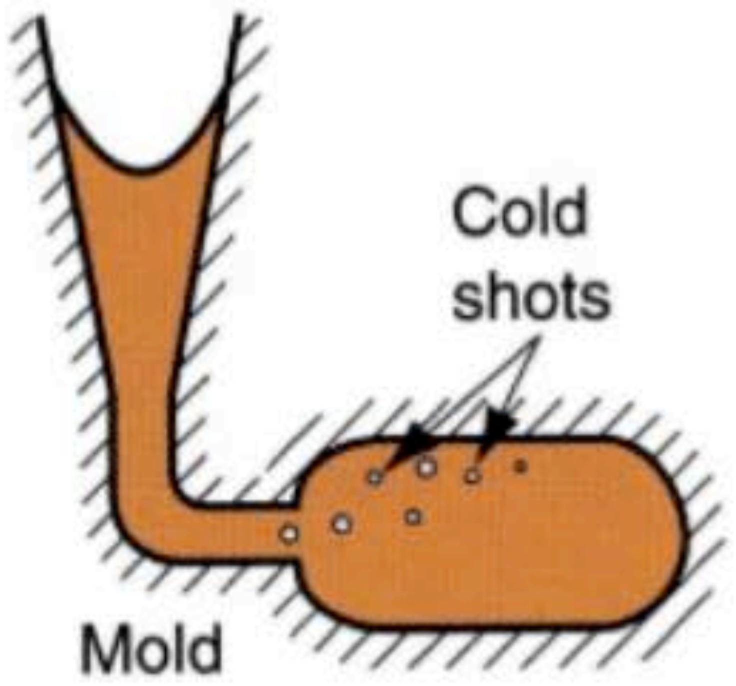
What causes the voids?

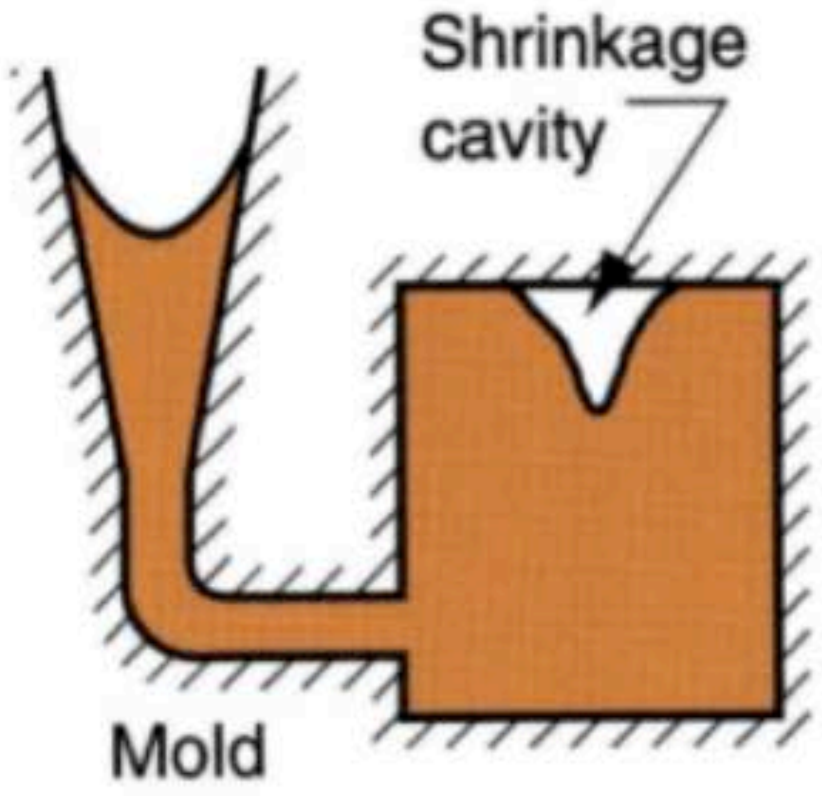
General Defects

- Misrun: solidification before complete filling
- Cold shut: lack of fusion due to premature freezing
- Cold shot: metal splatter entrapped in casting
- Shrinkage cavity: depression in surface caused by solidification shrinkage (or hot tear = internal void)



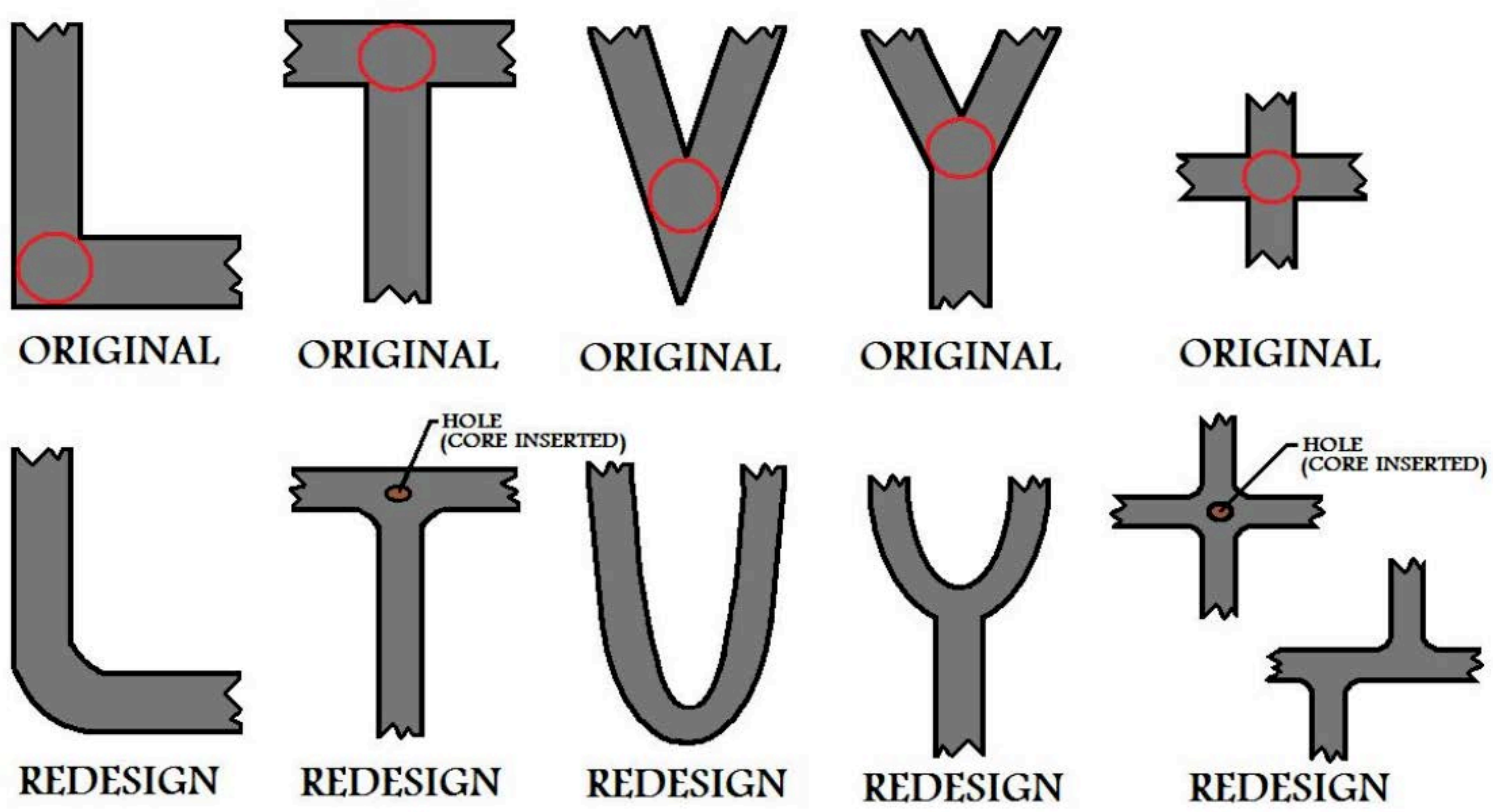






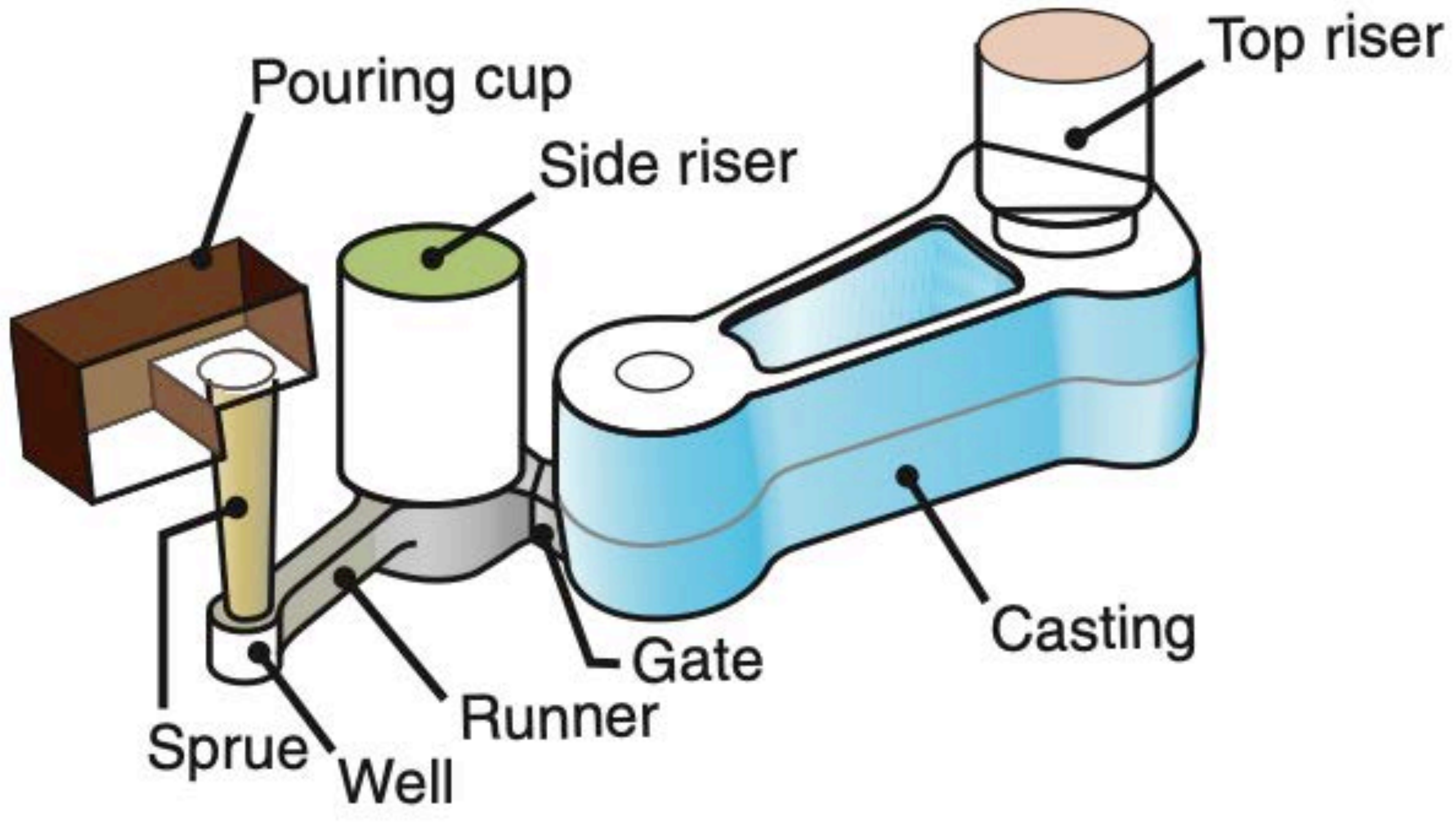
Geometric Considerations

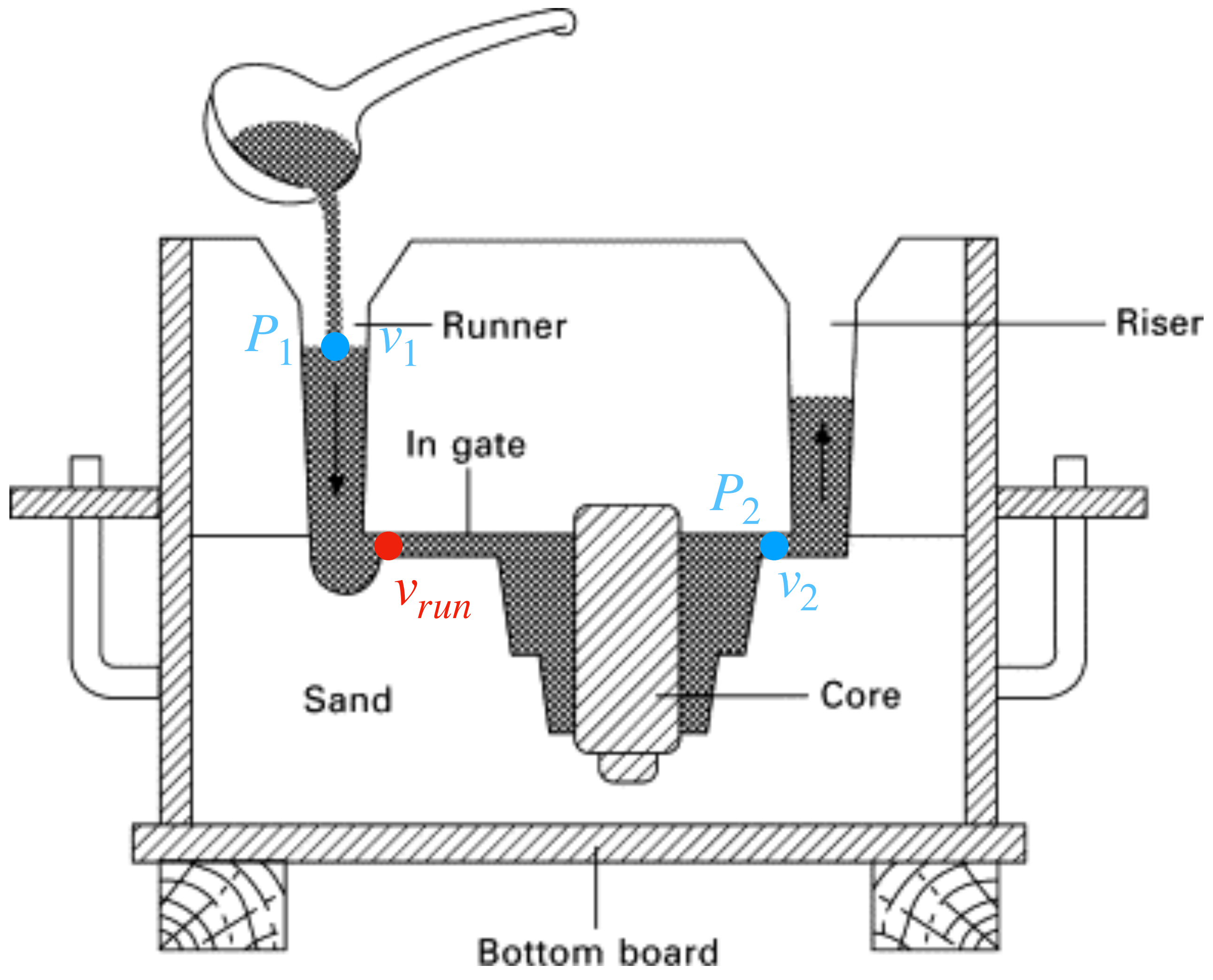
- avoid the development of hot spots



Sprue, Runner, and Gate Systems

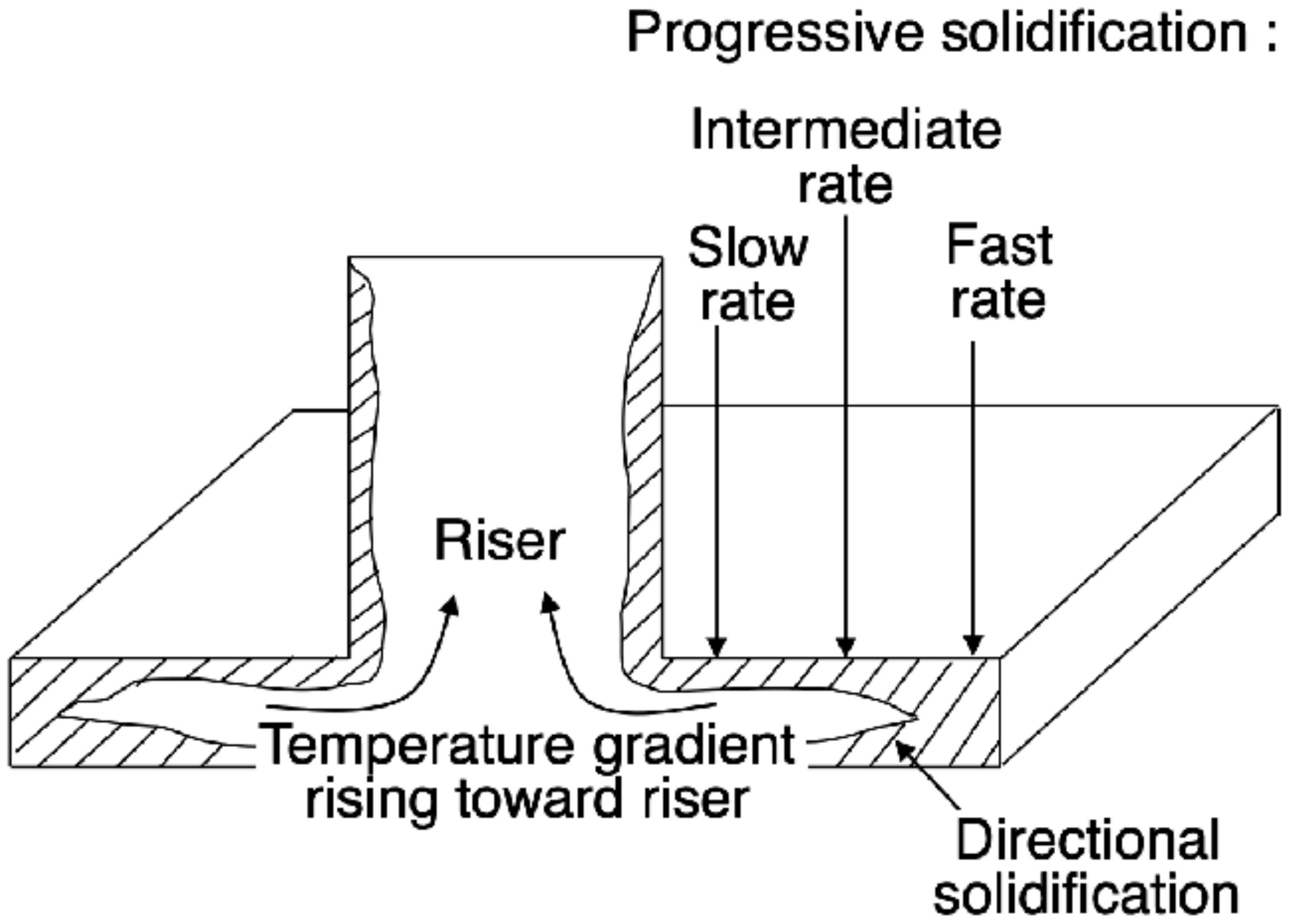
- rapid mold filling
- minimize turbulence
- avoid erosion
- remove inclusions
- control flow and thermal conditions
- minimize scrap and secondary operations

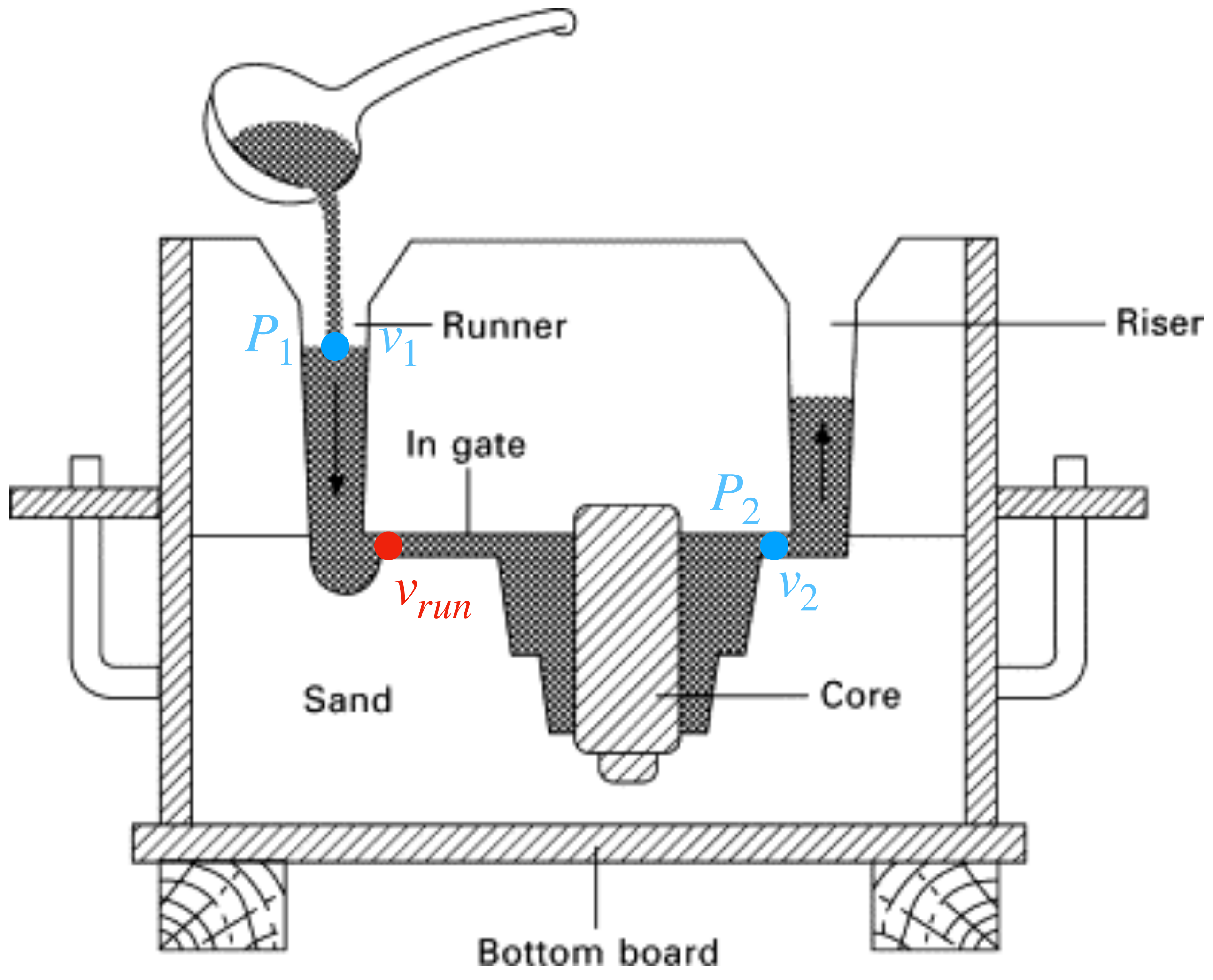




Risers

- location and size critical
- account for shrinkage (similar to "packing" in injection molding)
- directional solidification





Other Casting Methods: Investment Casting

Metals: Most castable metals.

Size Range: fraction of an ounce to 150 lbs..

Tolerances:
- ± .003″ to 1/4″
- ± .004″ to 1/2″,
- ± .005″ per inch to 3″
- ± .003″ for each additional inch

Surface Finish:
- 63-125RMS

Minimum Draft Requirements: None

Normal Minimum Section Thickness:
- .030″ (Small Areas)
- .060″ (Large Areas)

Ordering Quantities:
- Aluminum: usually under 1,000
- Other metals: all quantities

Normal Lead Time:
- Samples: 5-16 weeks (depending on complexity)
- Production 4-12 weeks A.S.A. (depending on subsequent operations).

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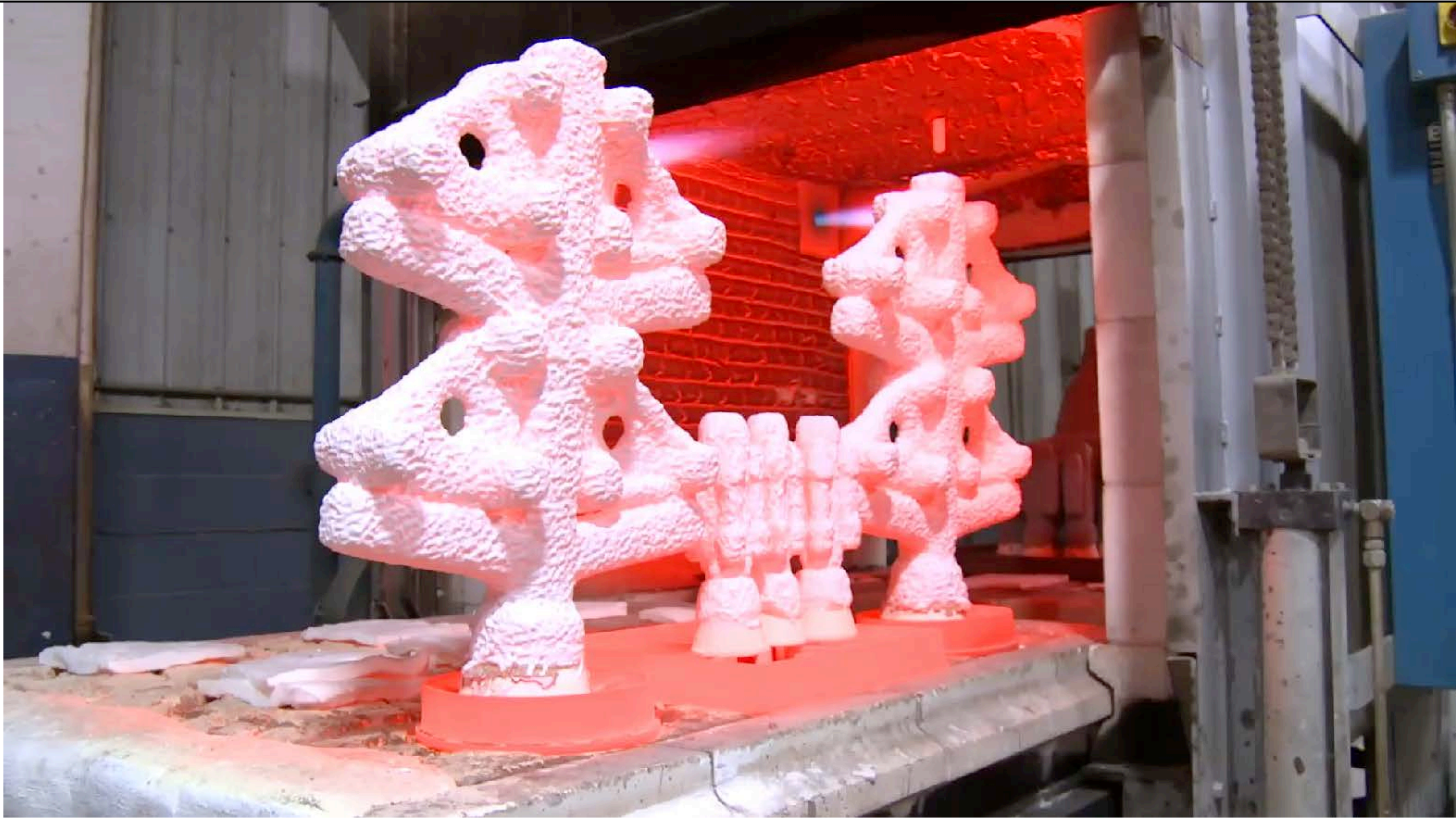
Investment Casting



Investment Casting

~4000 B.C.

- excellent surface finish with little post-processing

- use of ceramics allows for use of high melting point metals

- metal can be poured in a vacuum oven (to reduce defects)

- very labor intensive (automation) → jewelry, jet engine parts

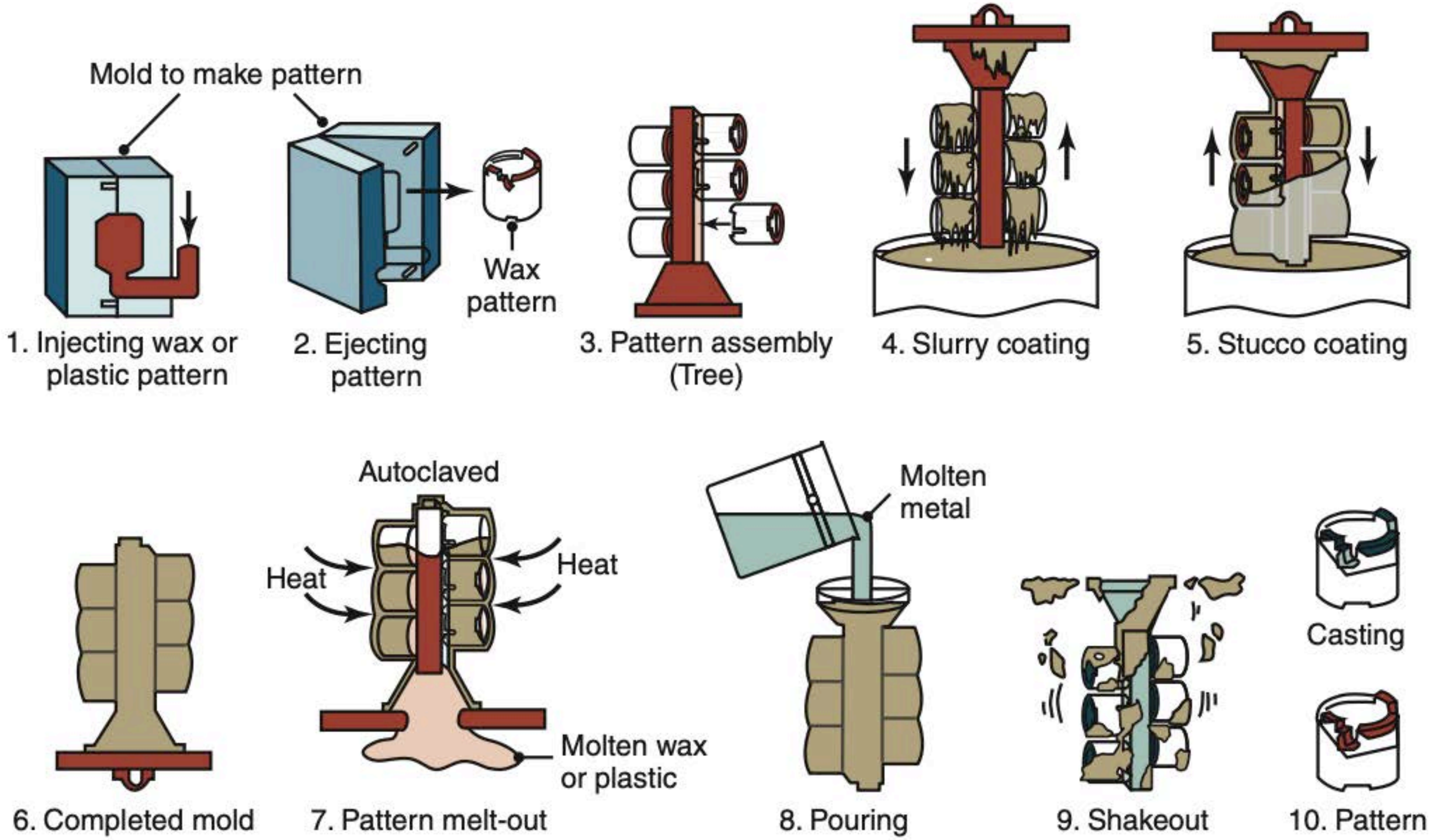


Figure 11.14: Schematic illustration of the investment-casting (lost-wax) process. Castings produced by this method can be made with very fine detail and from a variety of metals. *Source:* Courtesy of Steel Founders' Society of America.

Lost Foam Casting

Lost Foam Casting

- no parting line
- no cores
- more freedom in design
- minimum handling of sand
- ease of cleaning
- reduced effort for secondary operations

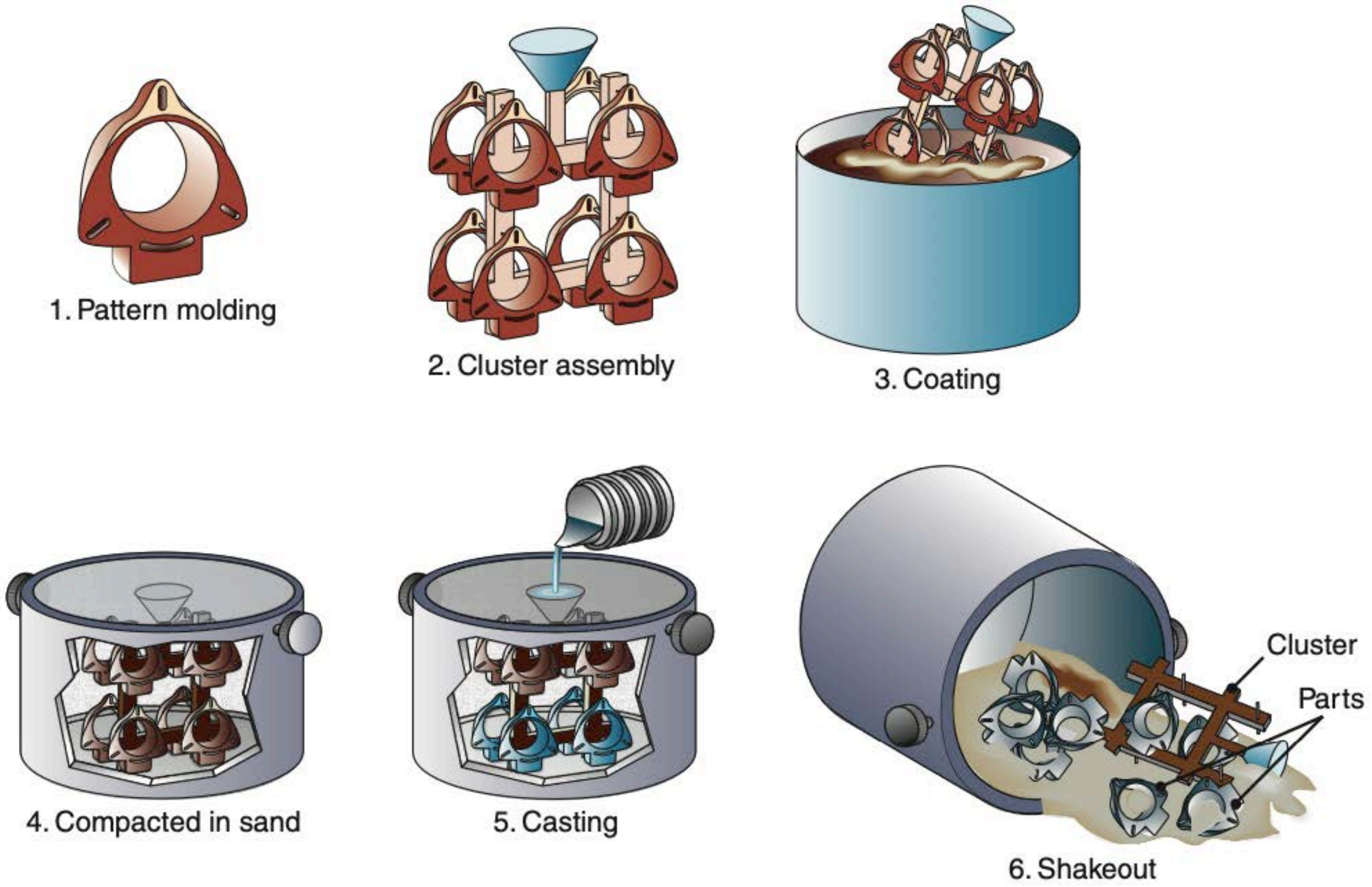


Figure 11.12: Schematic illustration of the expendable-pattern casting process, also known as lost-foam or evaporative-pattern casting.

Manufacturing Attributes

	Rate	Quality	Cost	Flexibility
Sand Casting	dependent on solidification $t_{solidify} = C\left(\frac{V}{A}\right)^2$	Tolerance (0.7~2 mm) and defects are affected by shrinkage Material property is inherently poor Generally have a rough grainy surface	tooling and equipment: ⬇ direct labor costs: ⬆ material utilization: ⬇ finishing costs: ⬆	High degree of shape complexity (limited by pattern)
Die Casting	dependent on solidification $t_{solidify} = C\left(\frac{V}{A}\right)^1$	Tolerance (0.08~0.2 mm) Mechanical property and microstructure depends on the method Good to excellent surface detail possible due to fine slurry	tooling and equipment: ⬆ direct labor costs: ⬇ to ~ material utilization: ⬆ finishing costs: ⬇	Ceramic and wax cores allow complex internal configuration but costs increase significantly
Investment Casting	dependent on solidification $t_{solidify} = C\left(\frac{V}{A}\right)^2$	Tolerance (0.02~0.6 mm) Good mechanical property and microstructure due to high pressure Excellent surface detail	tooling: **~ to** ⬆ equipment: ⬇ direct labor costs: ⬆ material utilization: ⬆	Low due to high die modification costs

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- Photo of bronze Herakles (Son of Zeus) is in the public domain.
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