



6.3

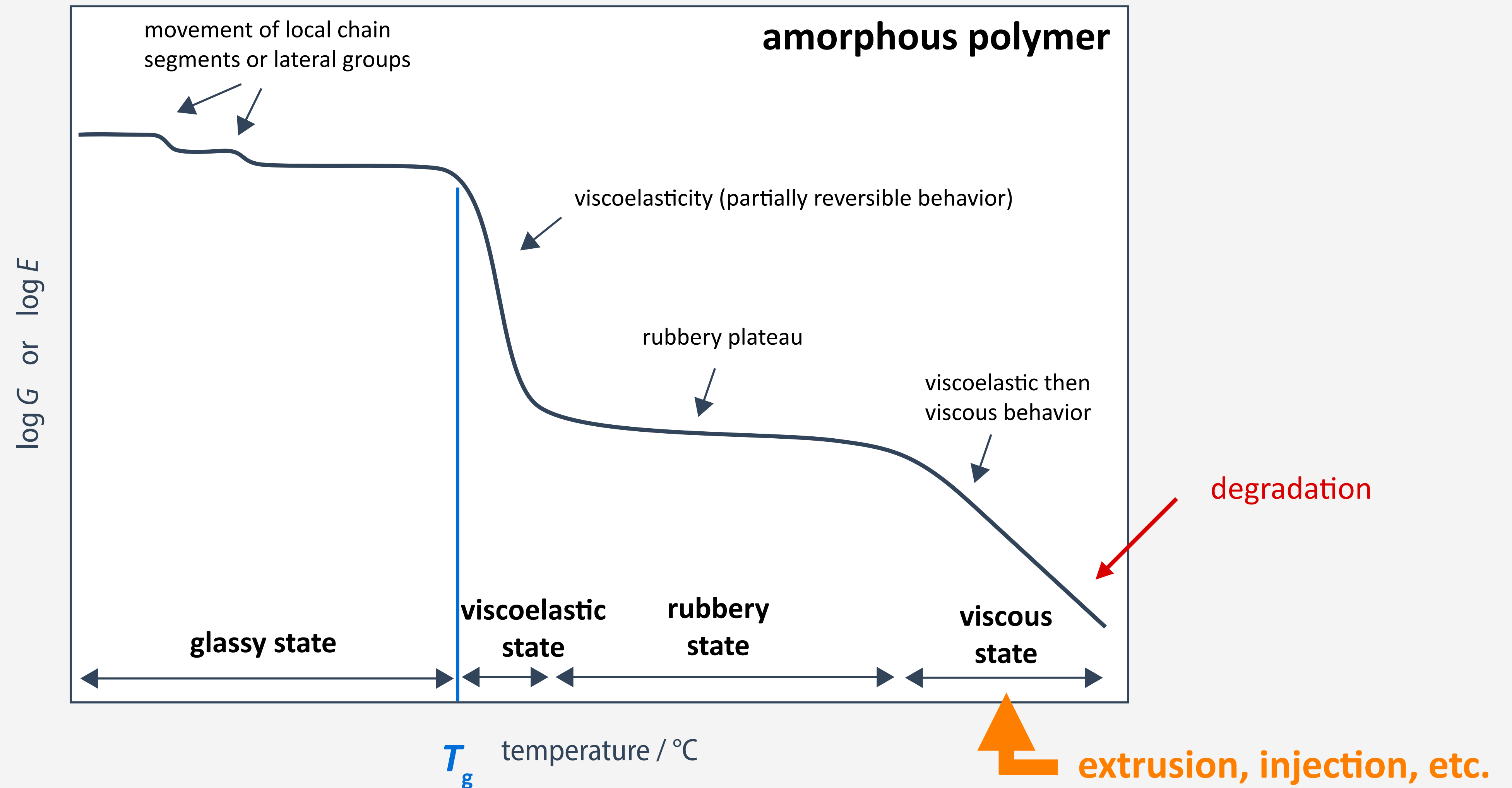
Processing Techniques



Extrusion

Behavior of an Amorphous Thermoplastic Material

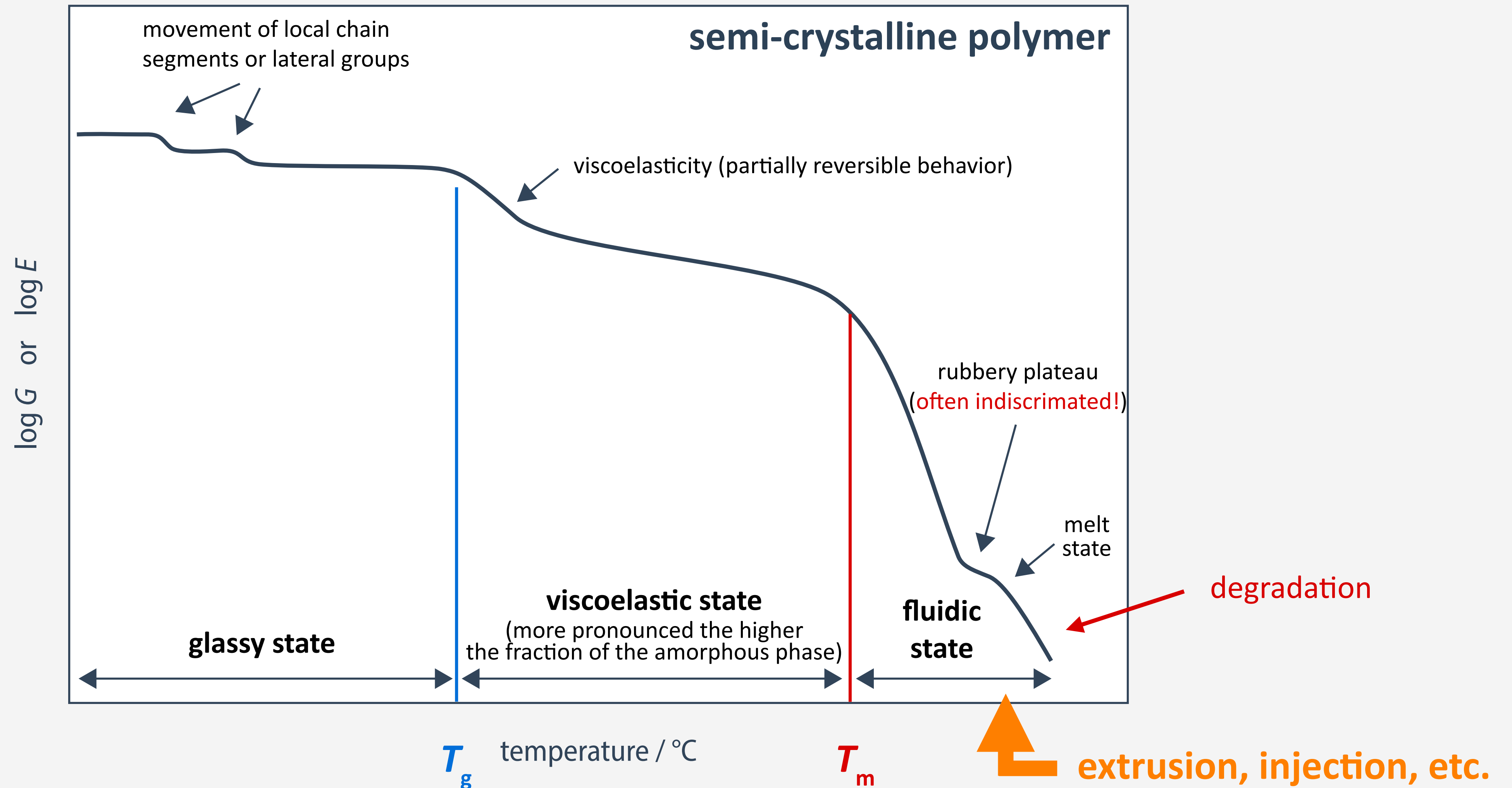
- extrusion-based approaches exploit the viscous nature of polymers



- operation T close to degradation onset often requires addition of stabilising additives (antioxidants)

Behavior of a Semicrystalline Thermoplastic Material

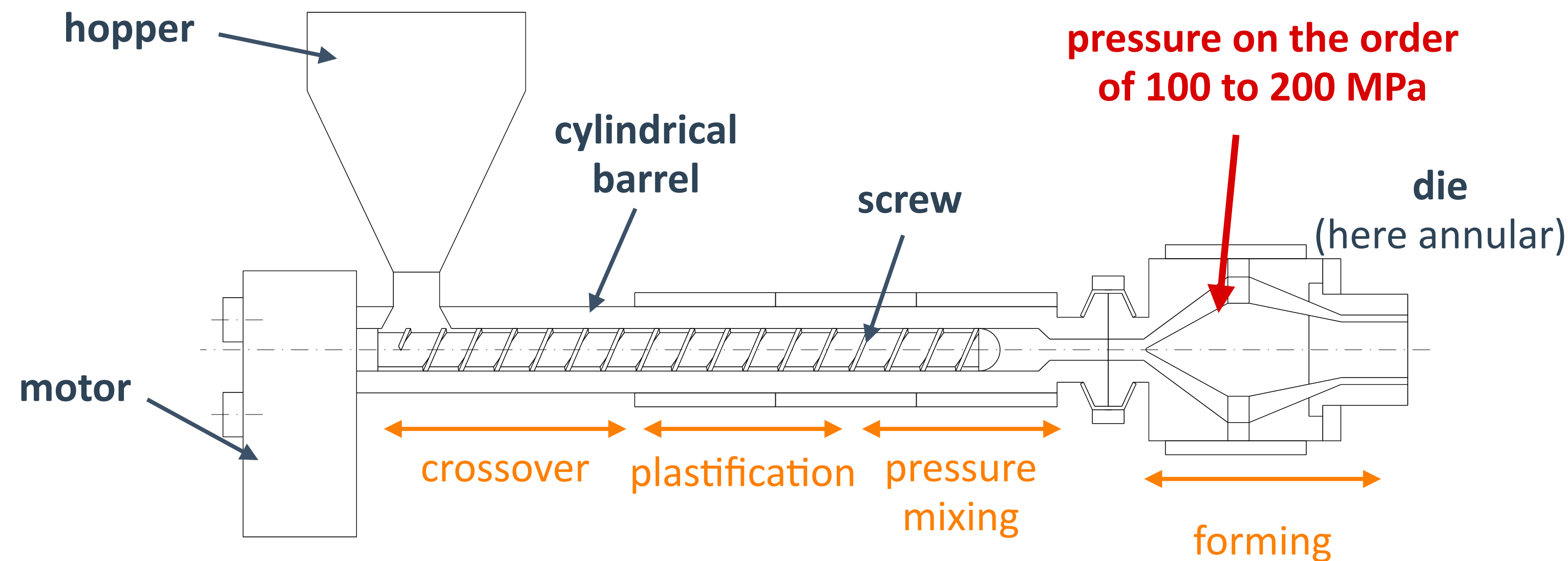
- extrusion-based approaches exploit the viscous nature of polymers



- operation T close to degradation onset often requires addition of stabilising additives (antioxidants)

Operation Principles of Extrusion

- processing technique for obtaining (semi-)finished products by a continuous process
- two main elements: a **plasticizing system unit** and a **die**

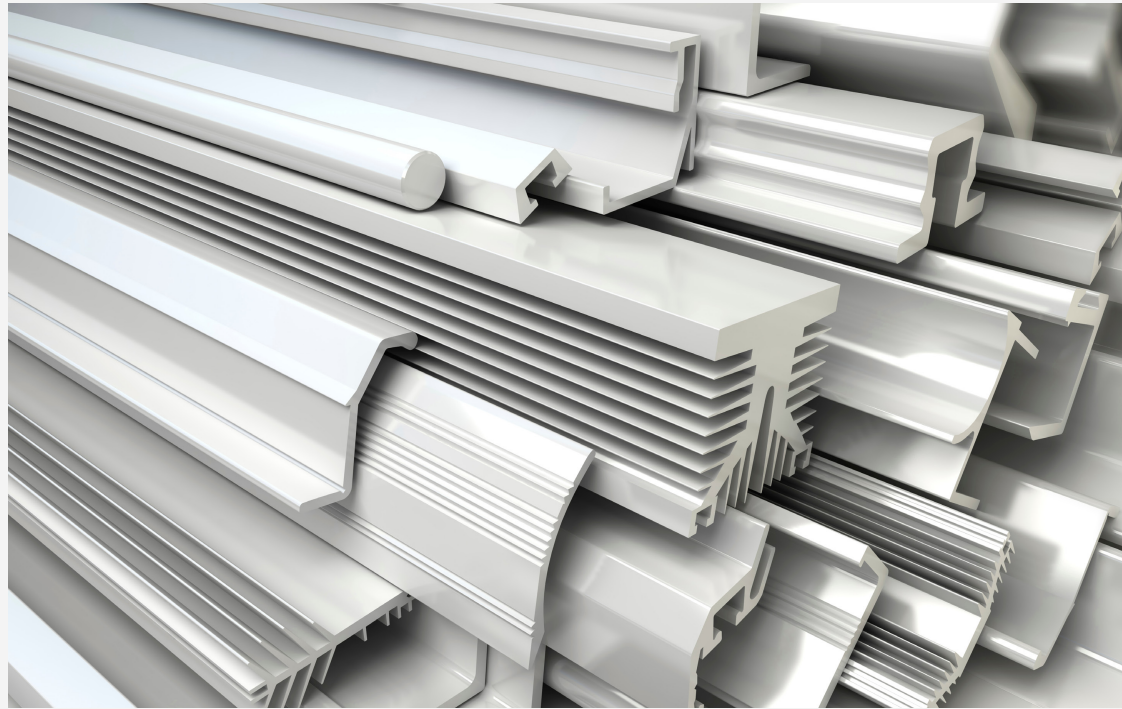


basic operation steps

- conveying of solid pellets and pushing towards the die by rotation of Archimedes' screws (feeding zone)
- melting/plasticization by friction and external heating (compression zone)
- homogenization/mixing (pumping zone)
- pressure generation
- shaping by the die

- often used for plastic formulations, i.e. mixing of polymer with additives followed by granulation (generally a 2-screw system is required: twin screw extruder)

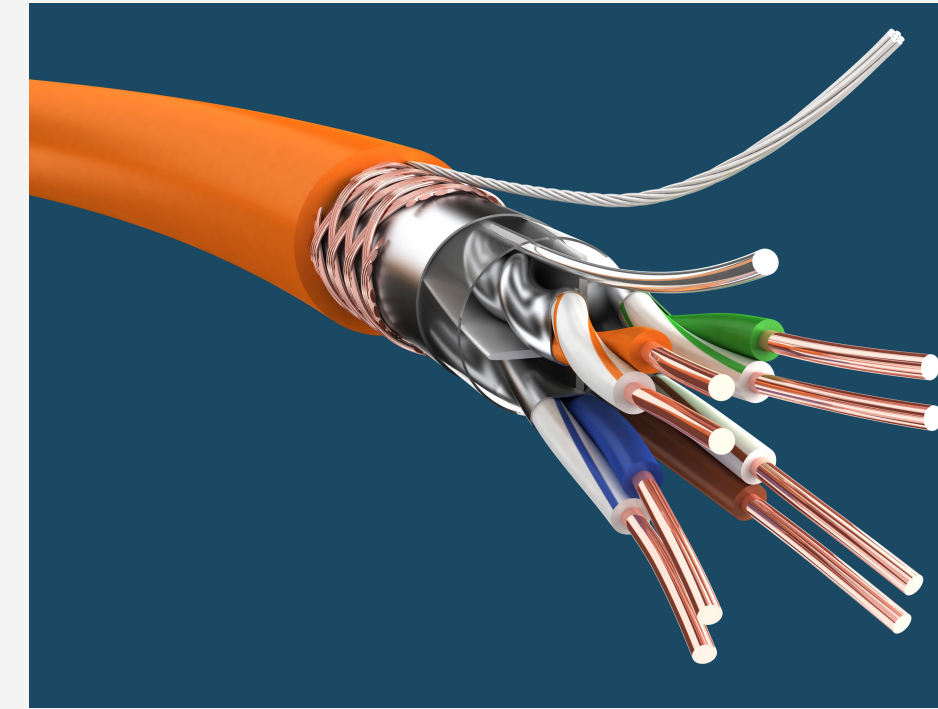
Main Categories of Extrusion Products



profiles



tubes



cable sheaths



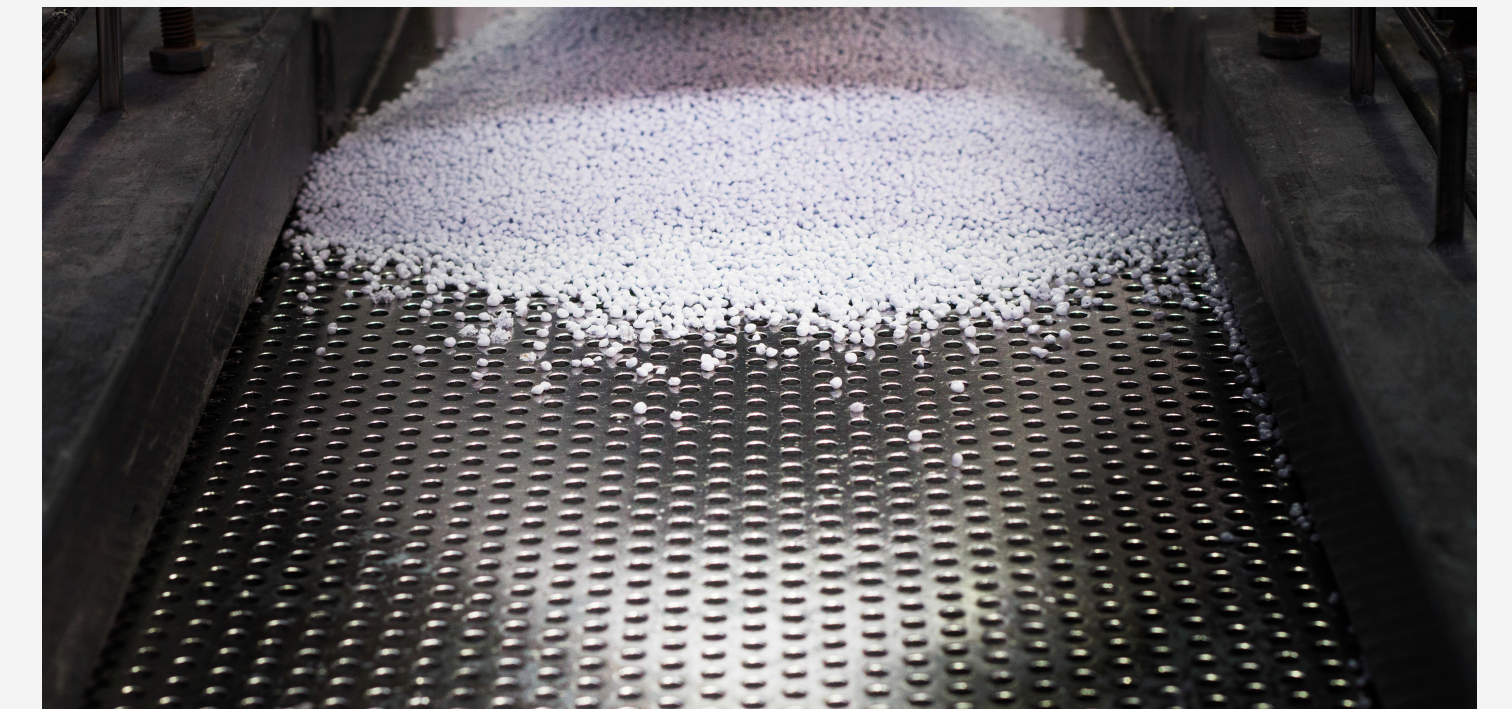
plates and sheets



textile fibres



hollow objects
(by extrusion blow molding)

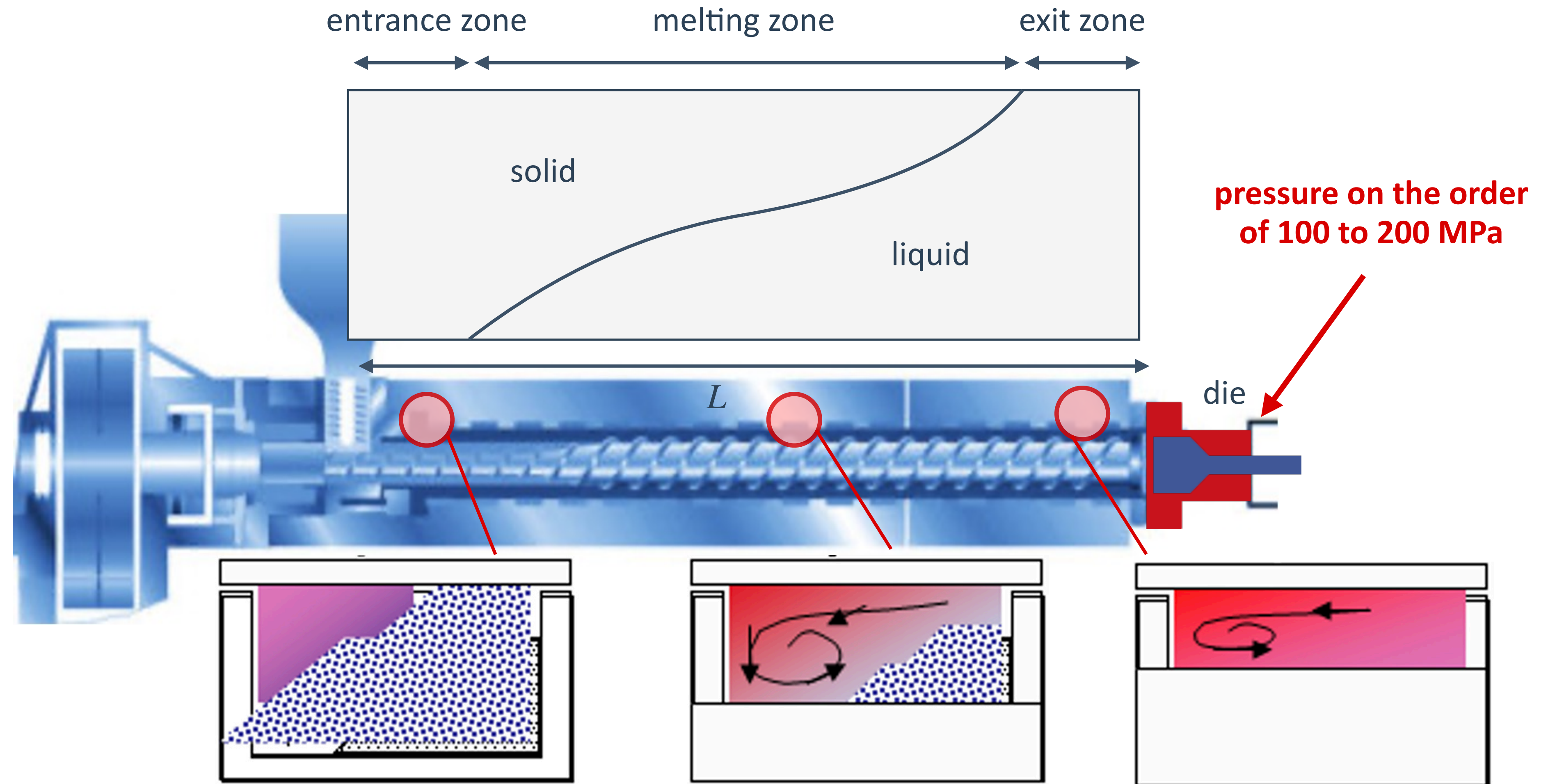


granules
(polymer + additive)

- techniques for plastic formulations, ogranules, plates, hollow preforms, injection molding, blow molding, inflation, thermoforming, and post-calendaring are all dependent on extrusion

Polymer State in the Barrel

- polymer granules pass from their solid phase into the melt state when pushed towards the exit zone



- pressure builds up until flow rates along the screw and through the die become equal

Extruder Flow

- **goal:** a maximum total flow rate, Q_T , for a minimised pressure difference, ΔP , to minimize the energy consumption by the screw drive

total flow rate

$$Q_T = Q_v - (Q_p + Q_f)$$

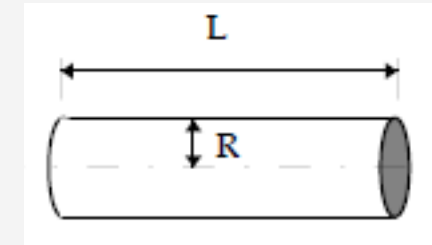
$$Q_v - Q_p = \frac{\pi^2 D^2 N H \sin \theta \cos \theta}{2} - \frac{\pi D H^3 \sin^2 \theta}{12 \eta} \frac{\Delta P}{L}$$

$$Q_{max} = \frac{\pi^2 D^2 N H \sin \theta \cos \theta}{2}$$

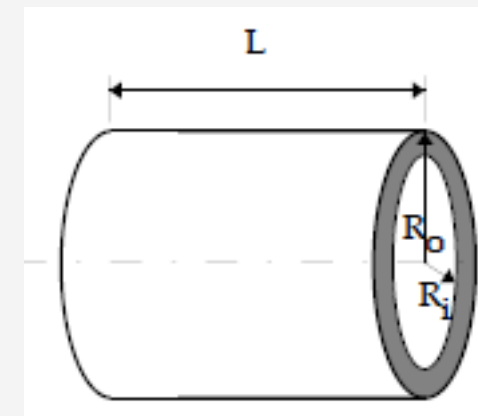
$$\Delta P_{max} = \frac{6 D L N \eta}{H^2 \tan \theta}$$

die flow

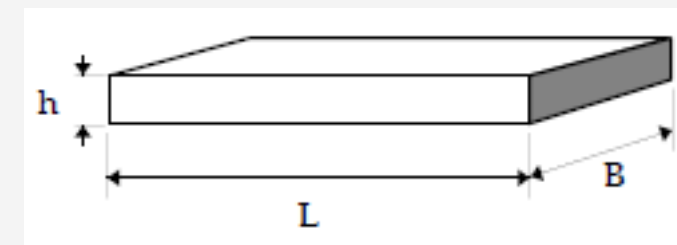
$$Q_{die} = k_d \frac{\Delta P}{\eta}$$



$$k_d = \frac{\pi R^4}{8l}$$

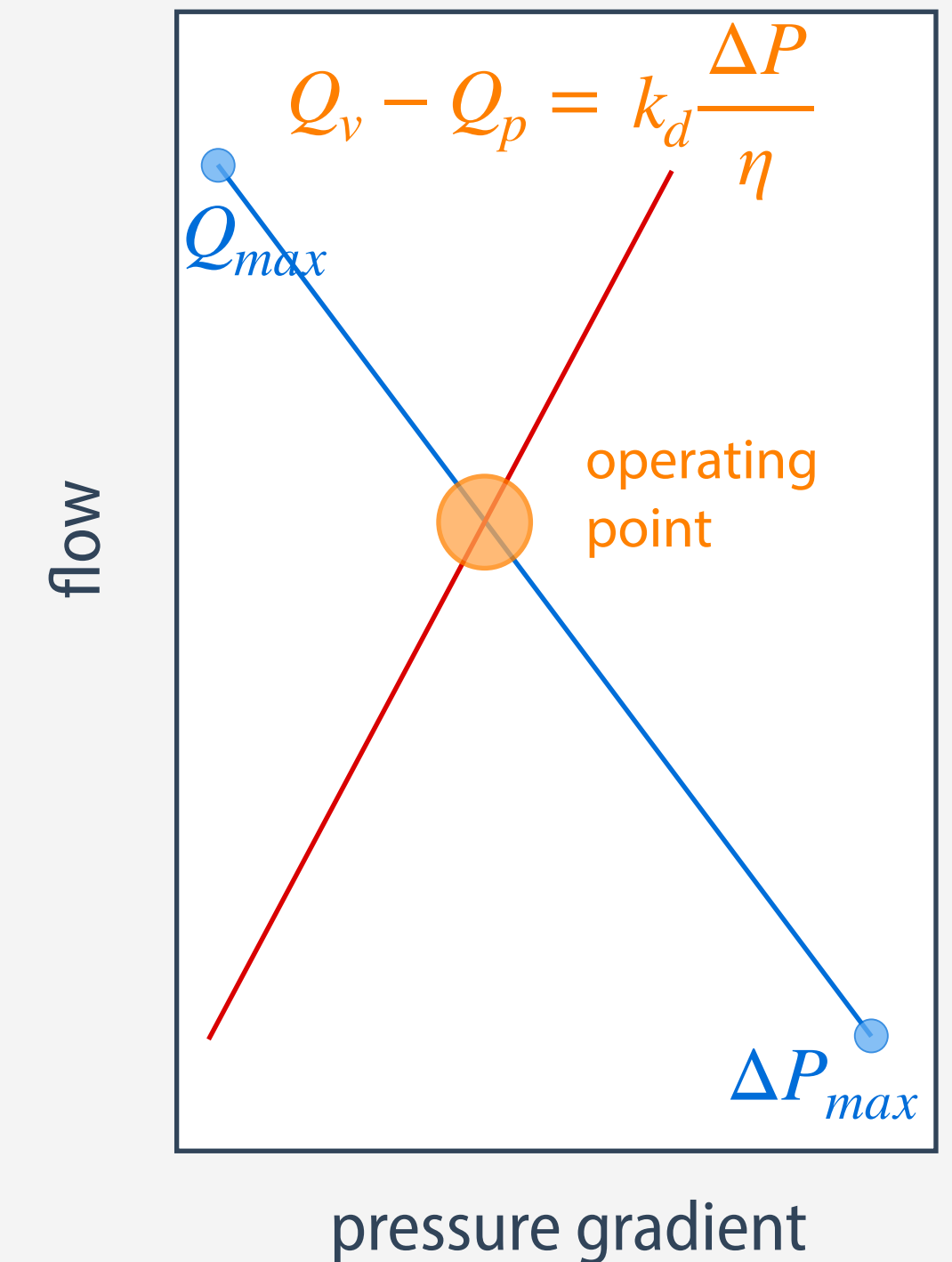


$$k_d = \frac{\pi (R_i + R_o)(R_o - R_i)^3}{12l}$$



$$k_d = \frac{B h^3}{12l}$$

operating point



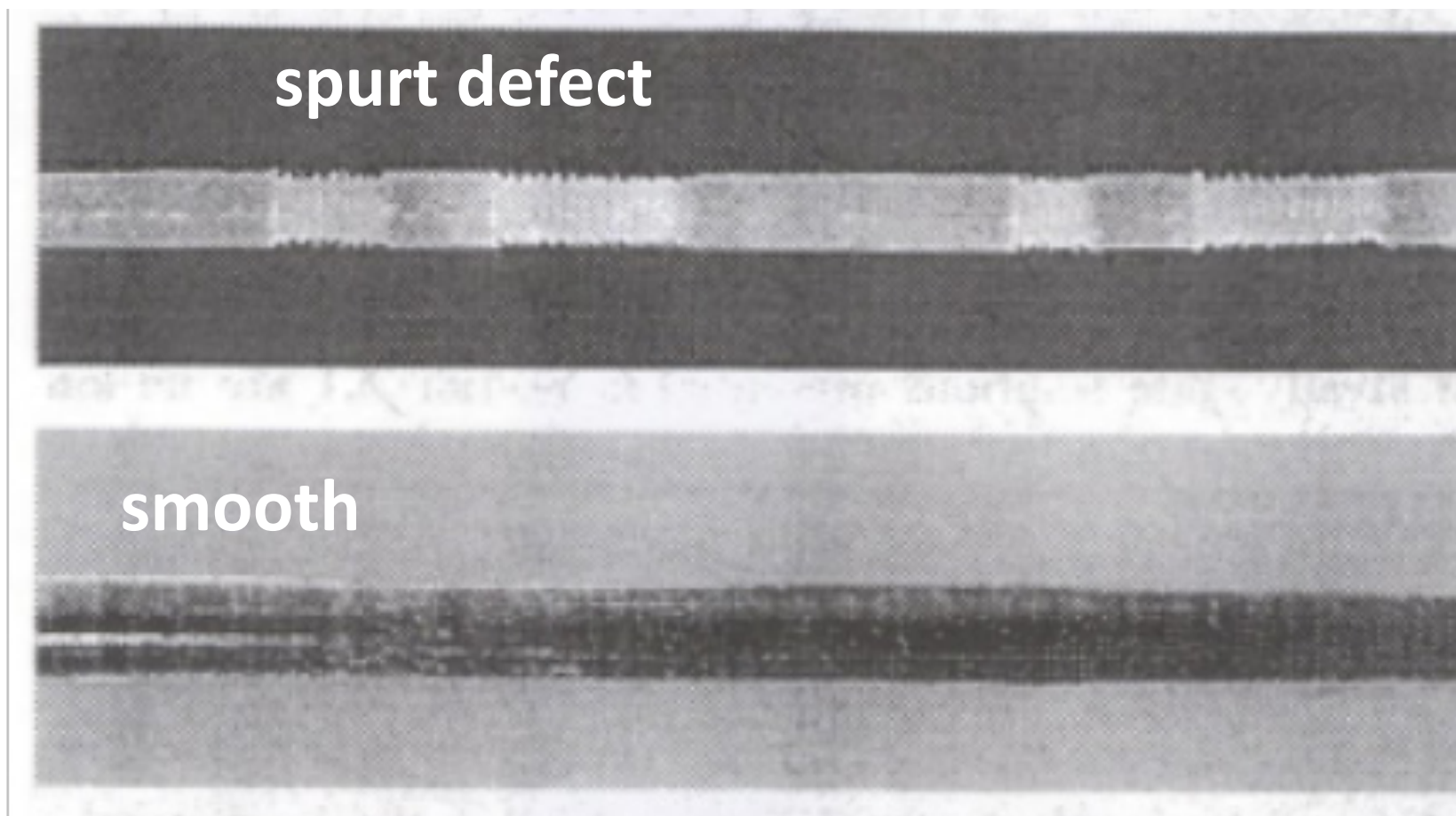
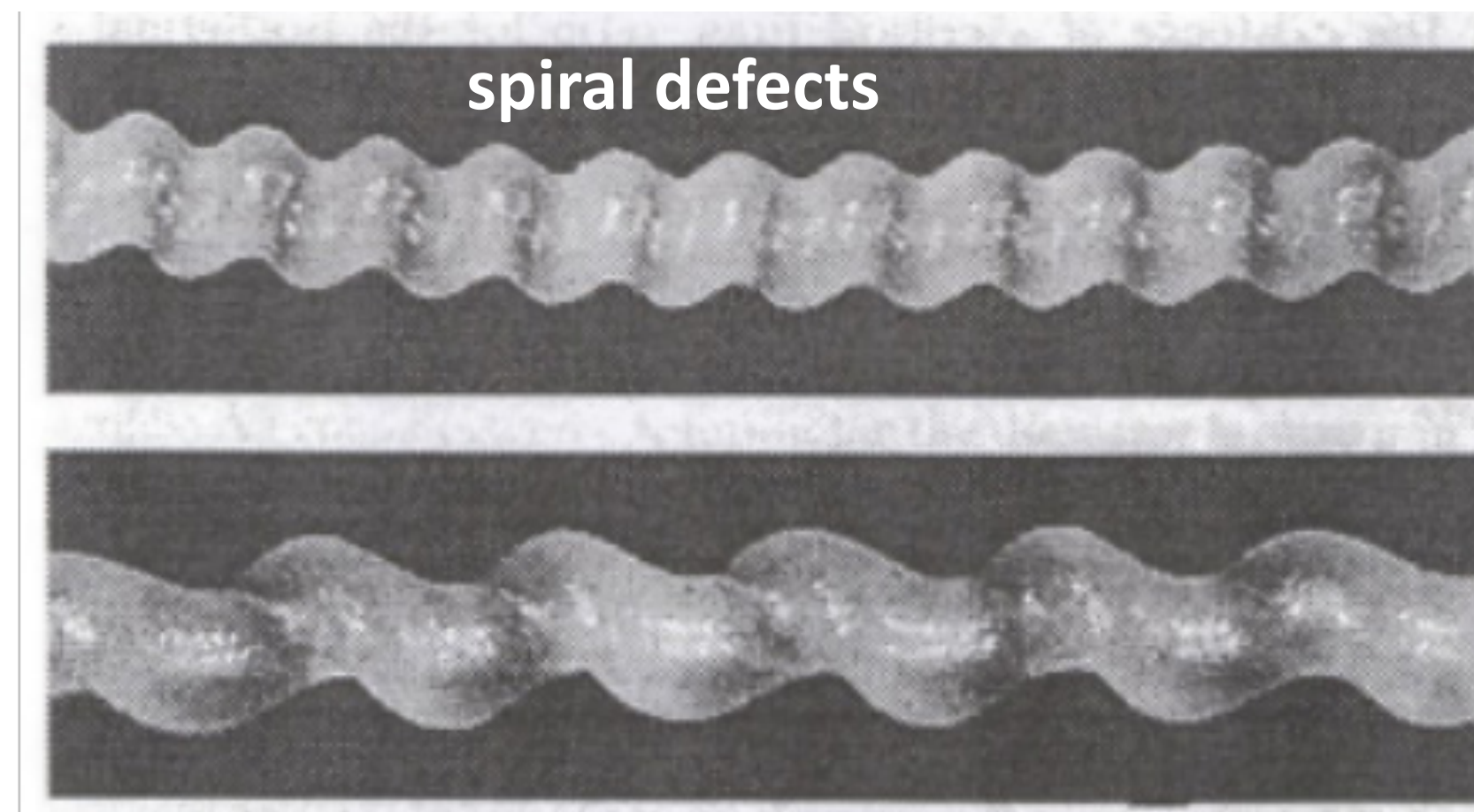
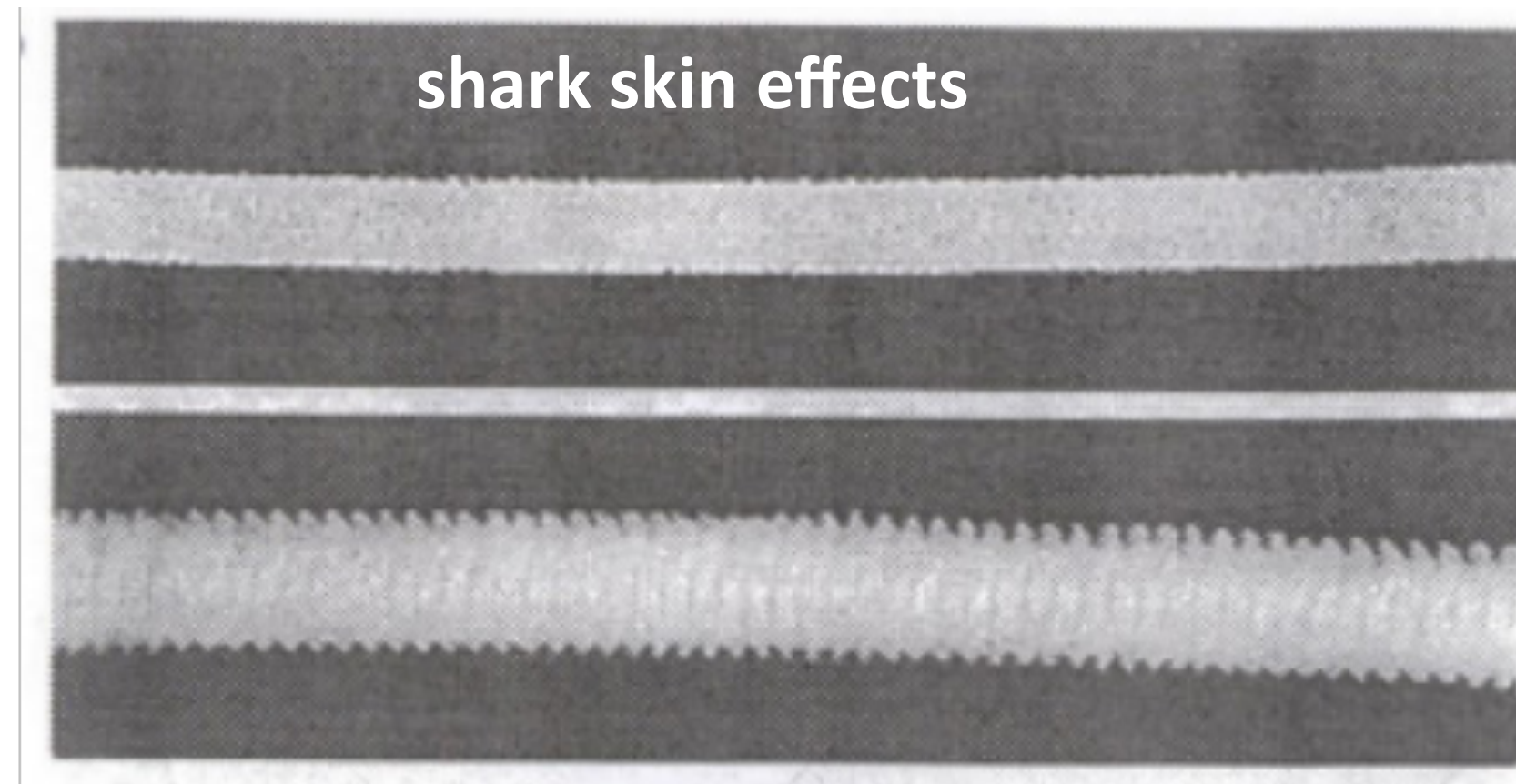
- **the operating point gives the flow rate and pressure of the extruder**

depends on rotation speed, N , screw diameter, D , channel height, H , screw length, L , thread angle, θ , and viscosity, η

- **die geometry & temperature are decisive for a good compromise between flow rate and energy cost**

Flow Instabilities

- particular importance of processing temperature because of its influence on viscosity



surface defects



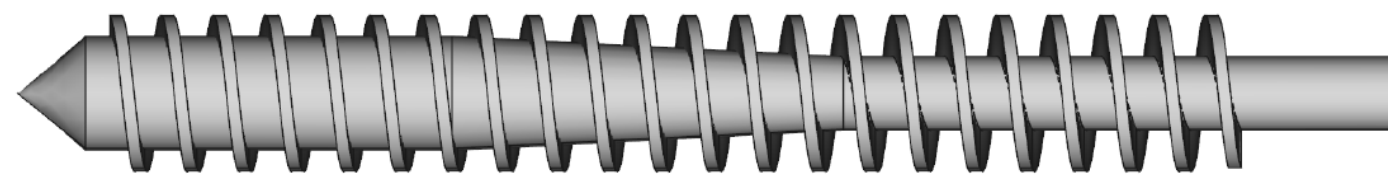
volume defects

- crucial for product quality; requires careful adjustment of polymer properties by additives (i.e. lubricants)

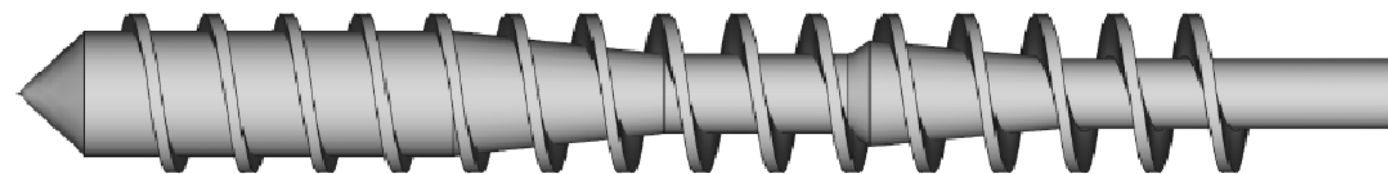
The Screw

- most important element of the extruder
- generally characterised by a body diameter that increases from the back to the front

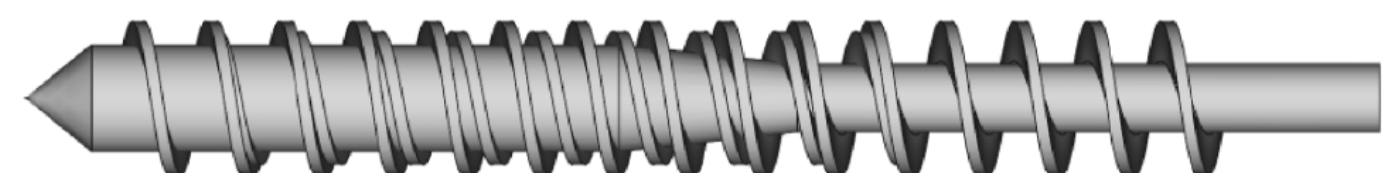
important screw types



3-zone screw



degassing screw

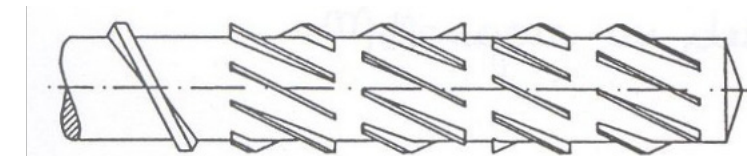


barrel screw

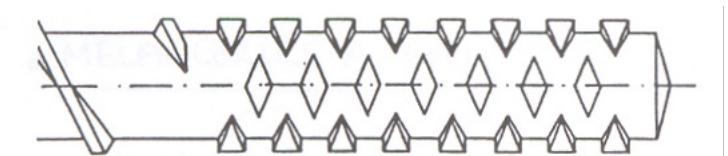
twin screws



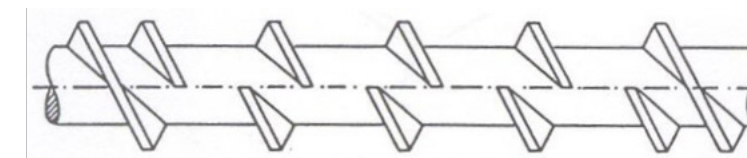
other screw geometries



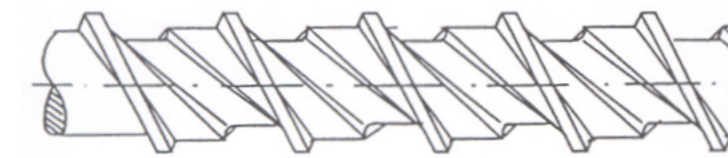
SAXTON screw
(low pressure loss,
improved transport)



PINEAPPLE screw
(better flow,
no flow line breaks)



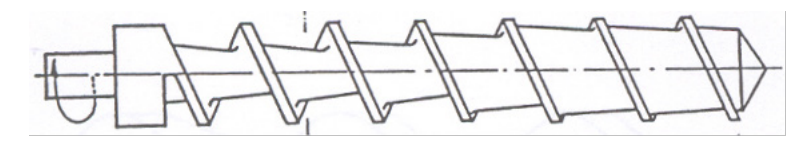
OMD-Rheotec screw
(better mixing,
less plasticization)



PULSAR screw
(little breakage,
more reorientation)



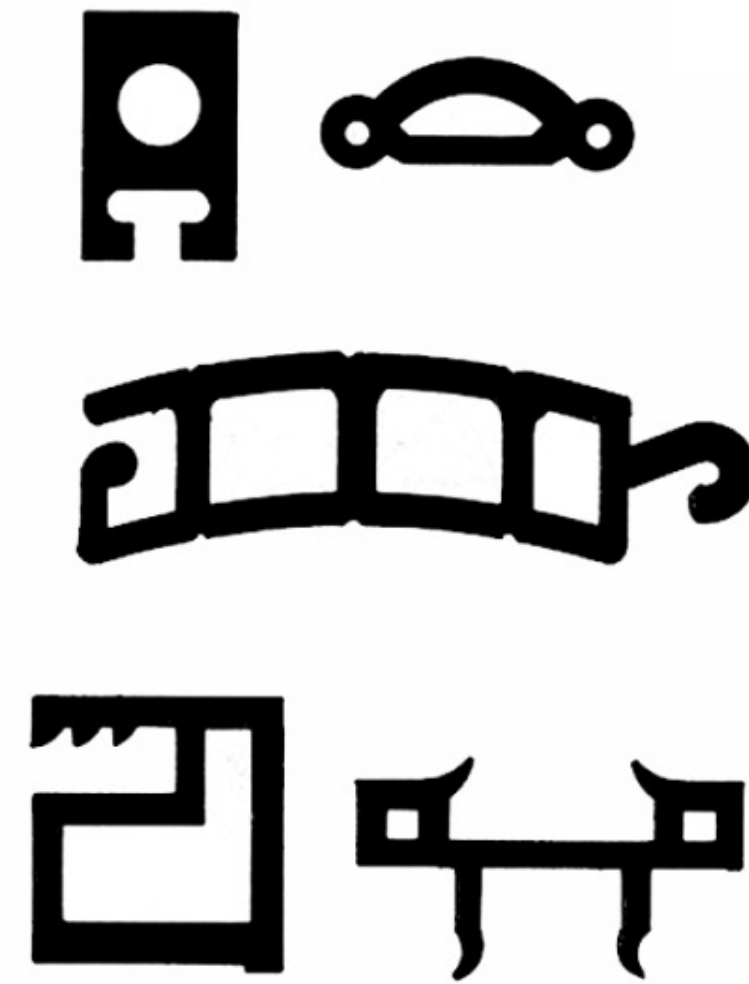
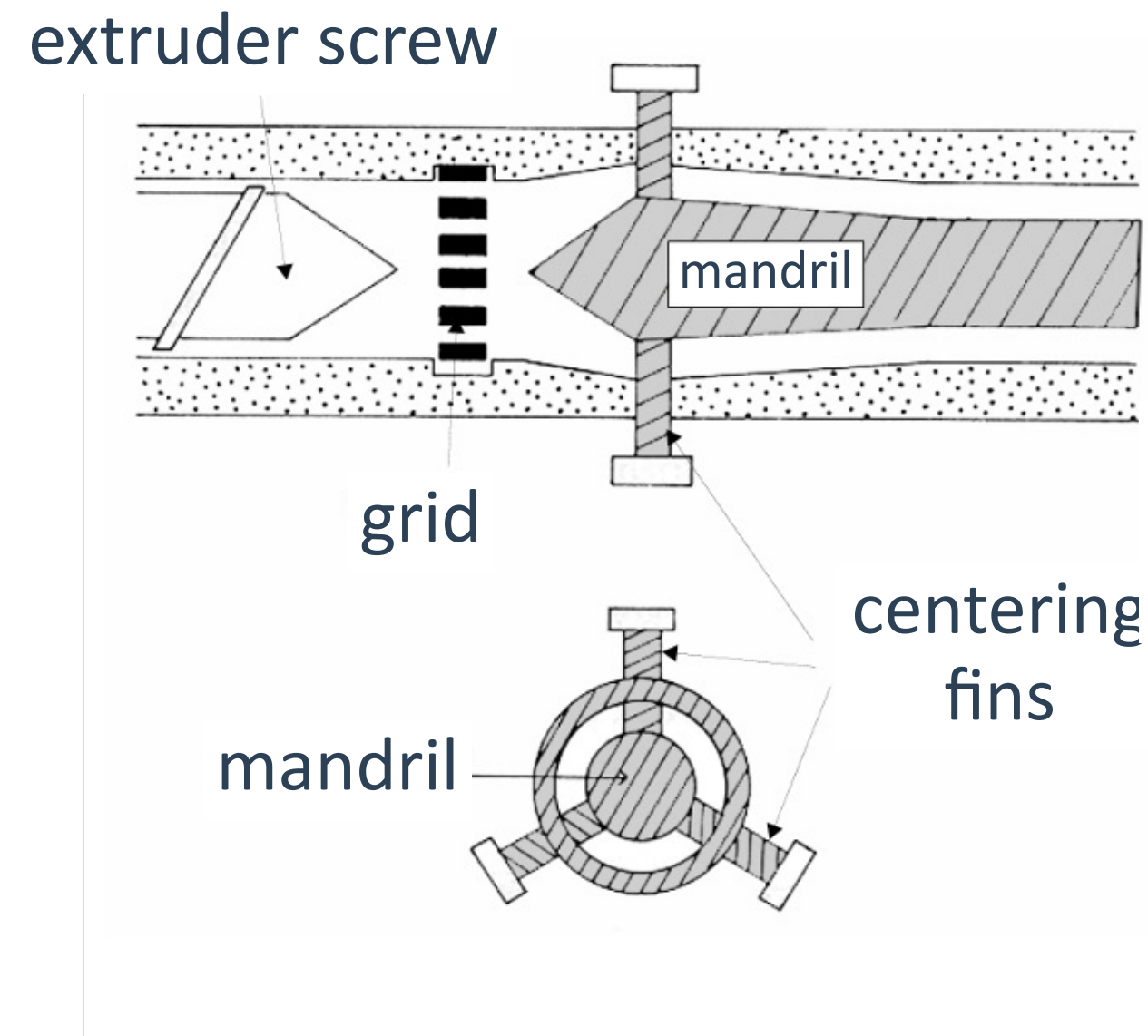
STRATA screw
(little breakage,
reorientation)



COHEN screw
(improved melting
and mixing)

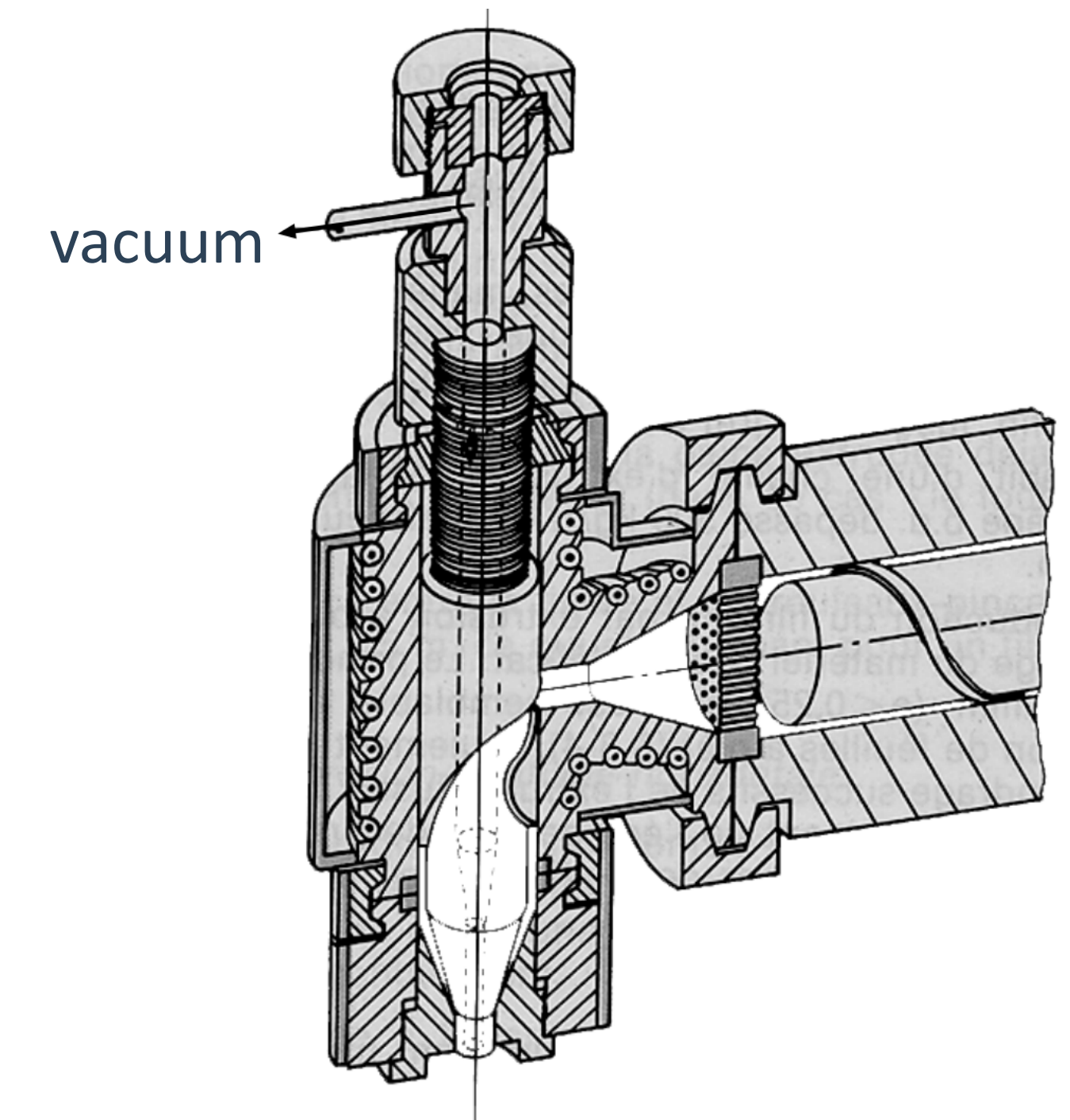
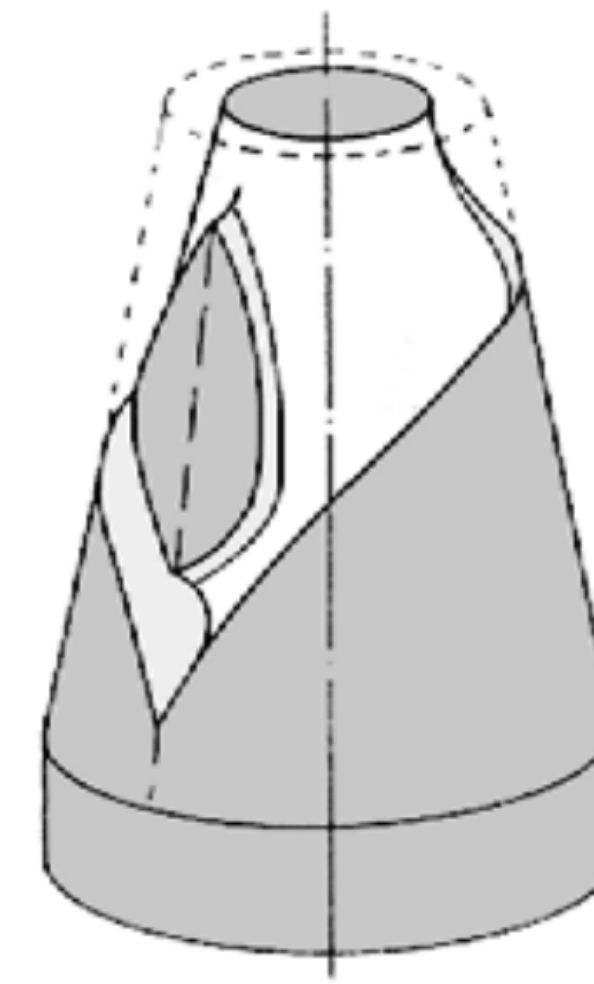
The Die

straight dies



- for extrusion of profiles, tubes, or plates

square dies

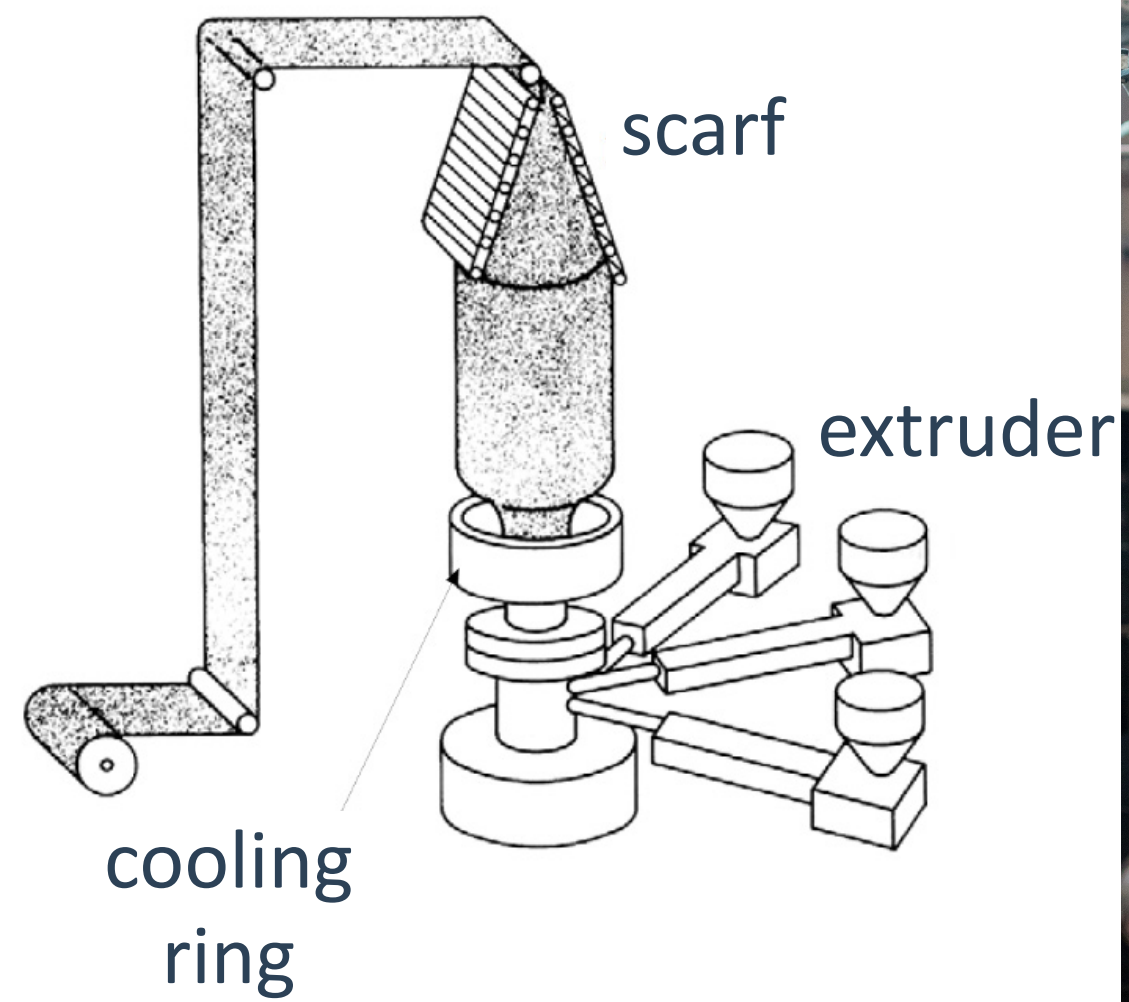


example: cable sheathing

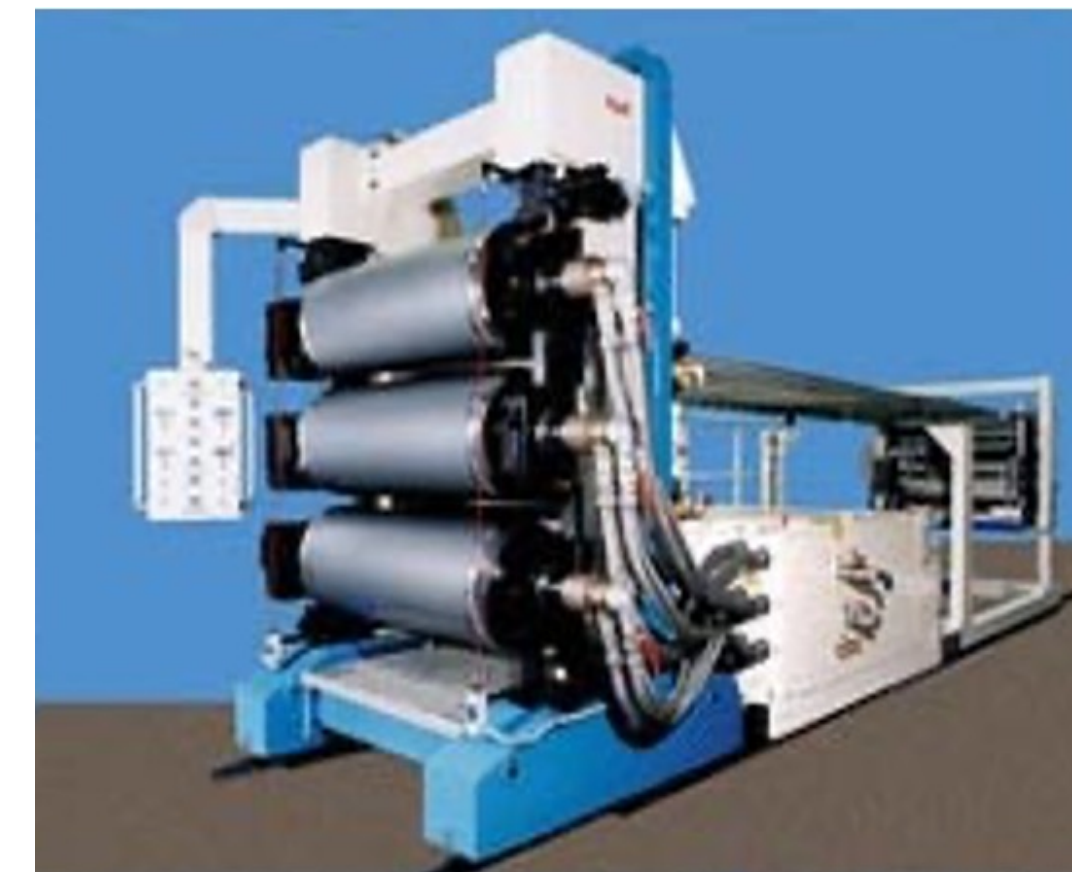
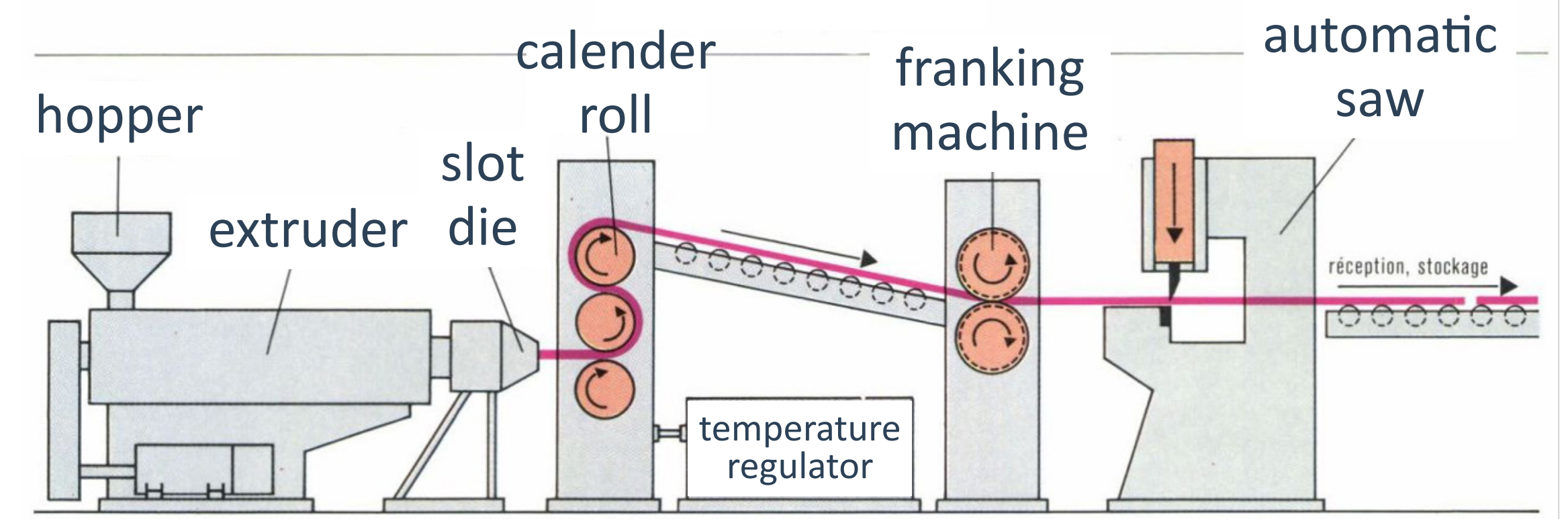
- for plastic inflation, extrusion blow molding, cable sheathing

Post Transformation

inflation of thin sheets (plastic bags)

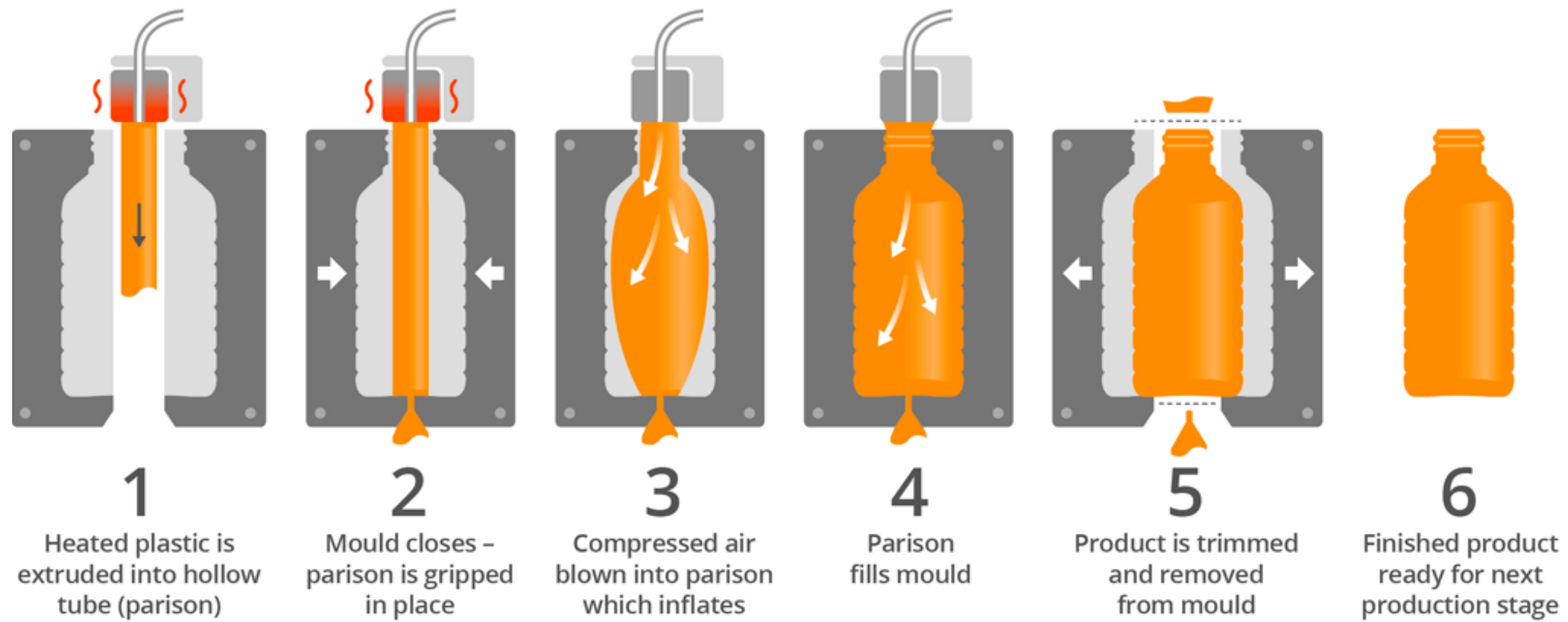


calendering

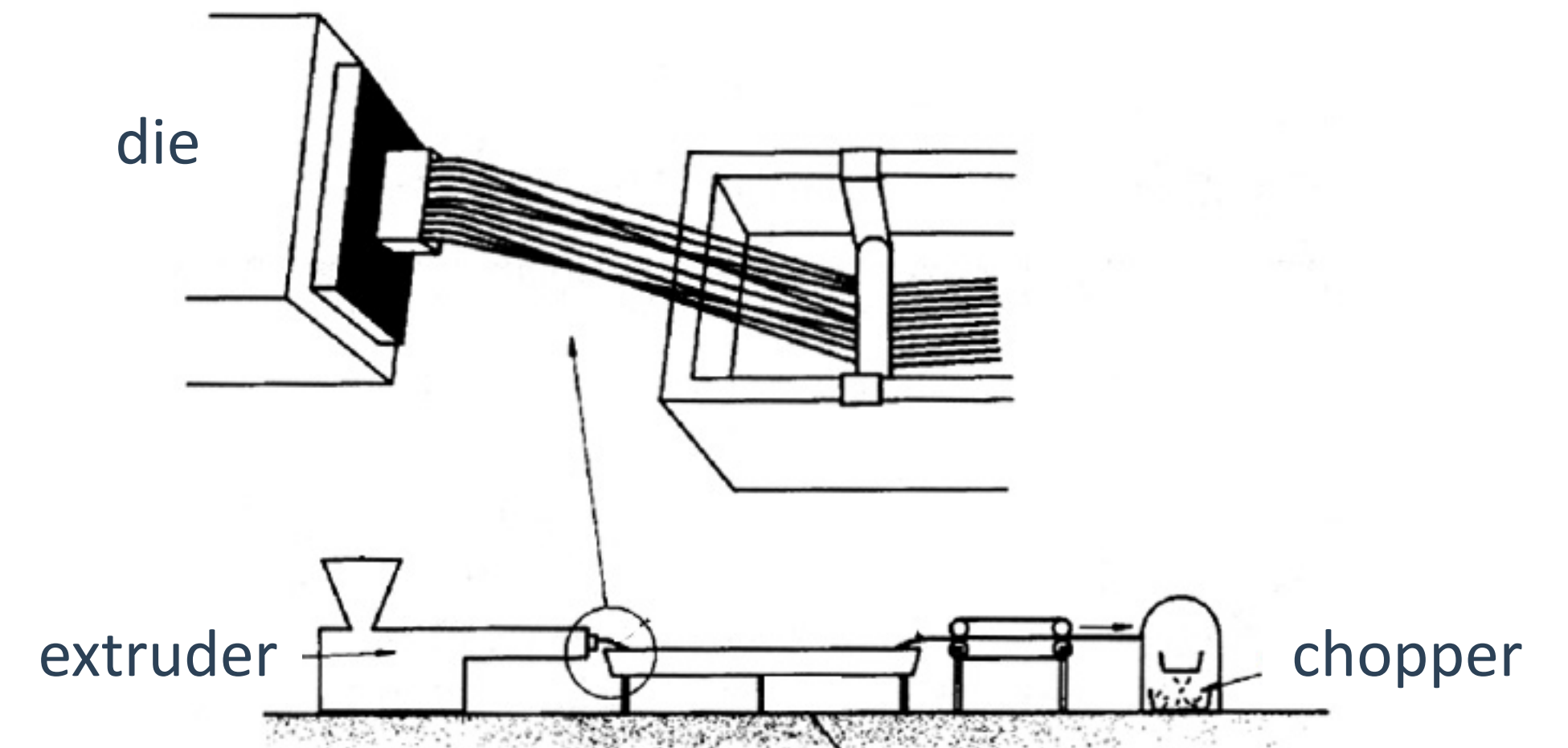


Post Transformation

extrusion blow molding



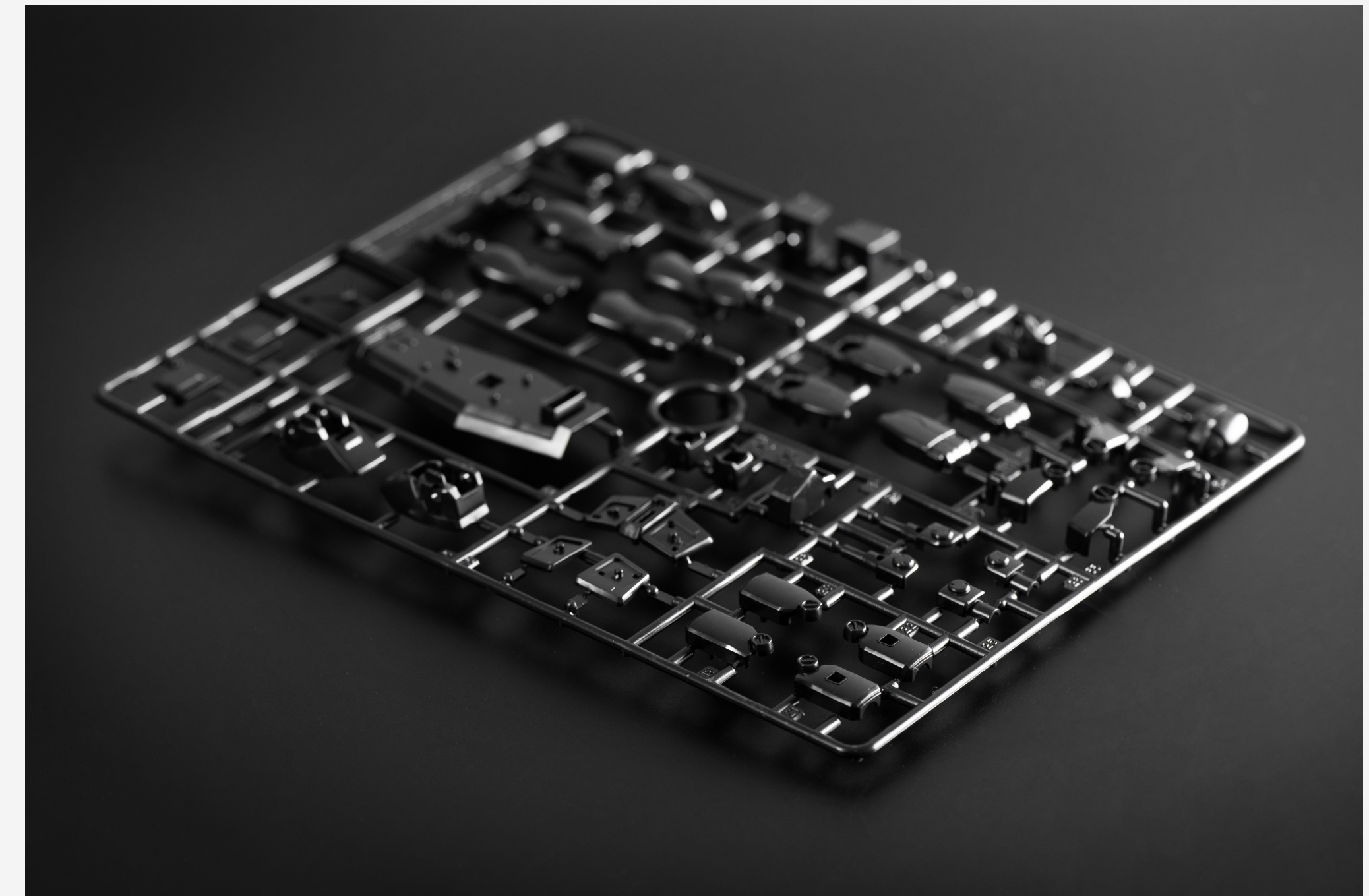
granulation



Injection

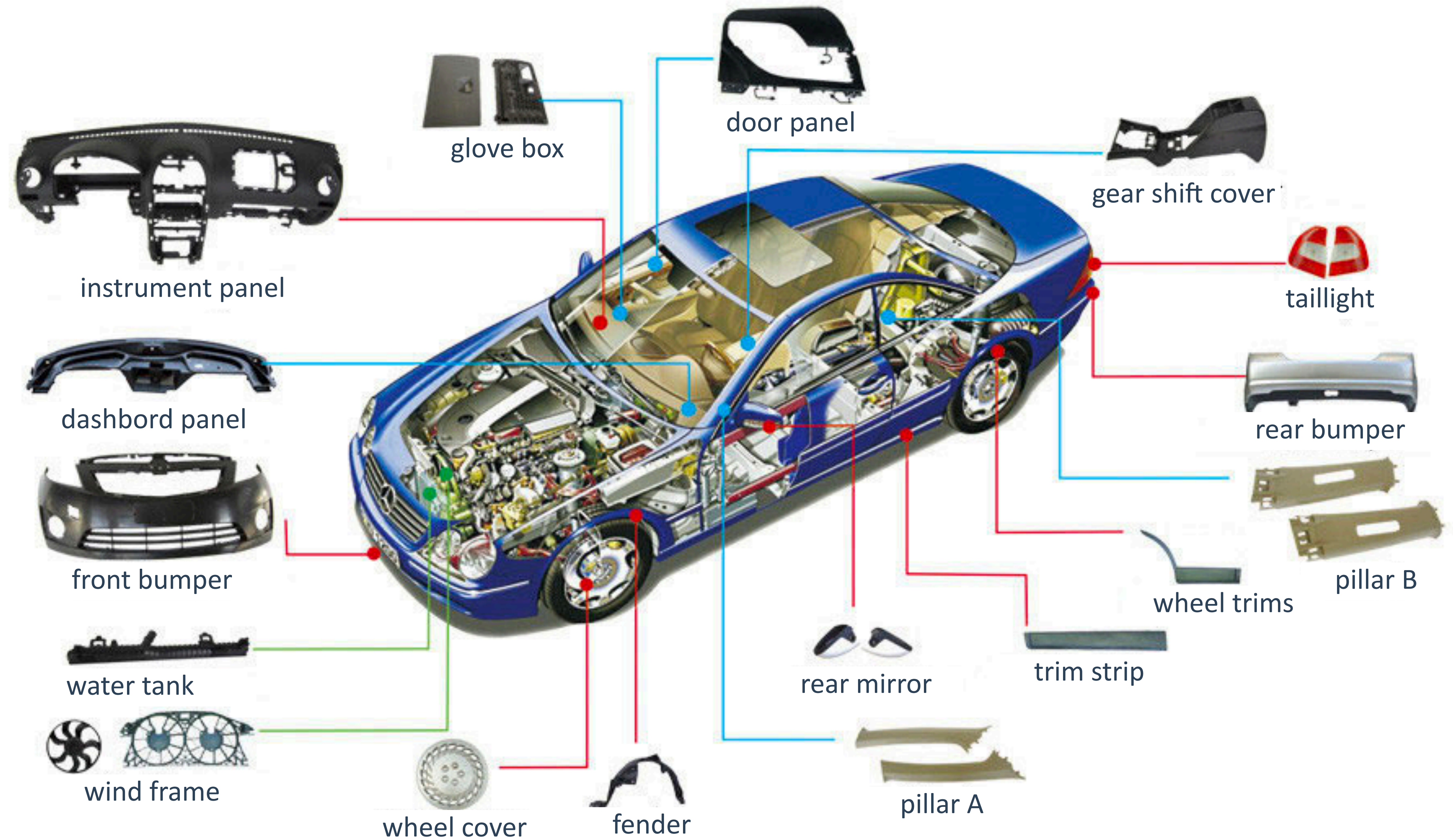
Injection Molding

- manufacturing of a piece in series
- great design freedom compared to other processing techniques
- however, limited to the less rigid plastic materials (hardly compatible with fiber reinforcement)



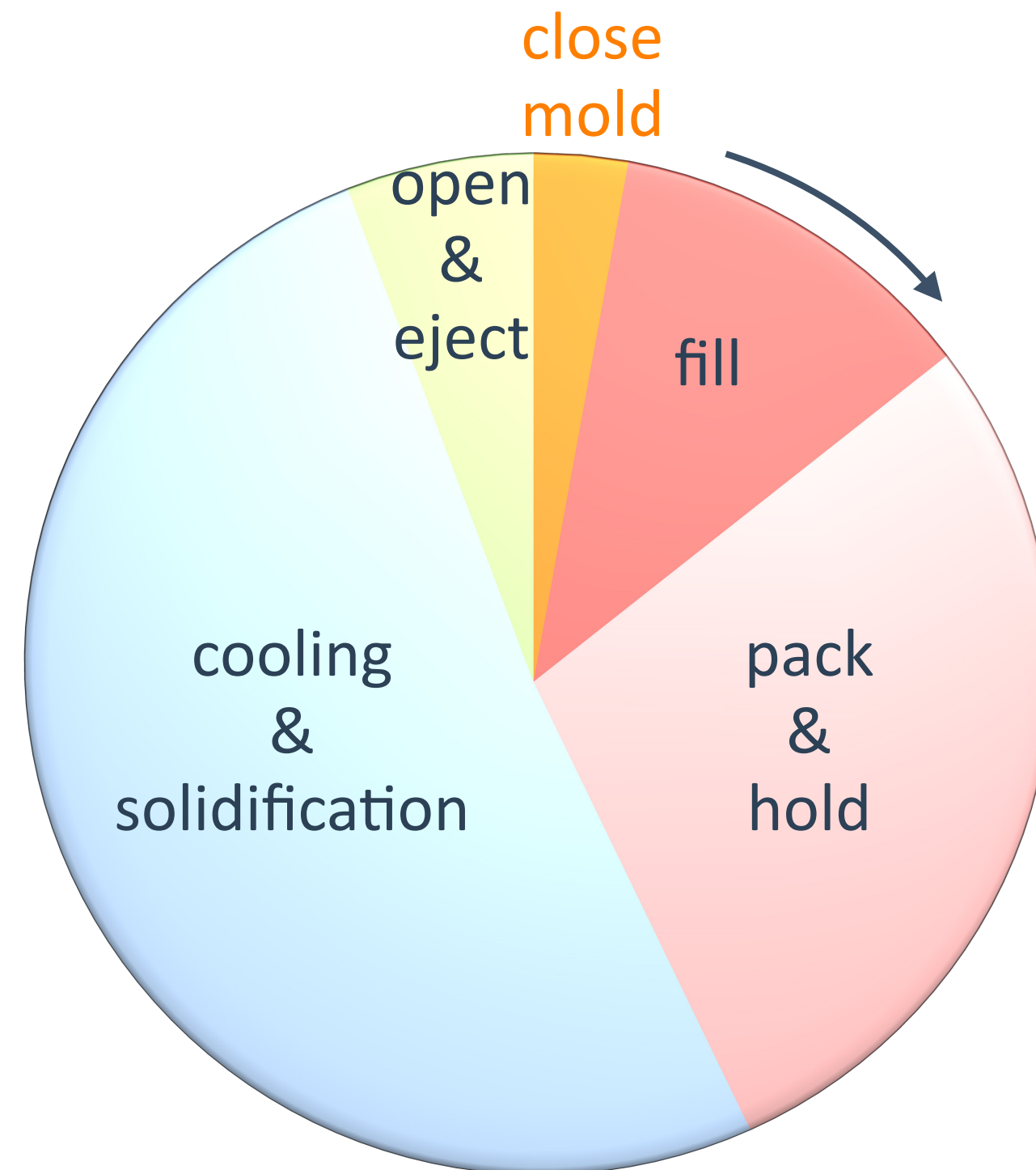
- Main application in automobiles, electronics, robotics, aerospace, phones, household appliances, medical...

Injection Molding for Automotive Parts

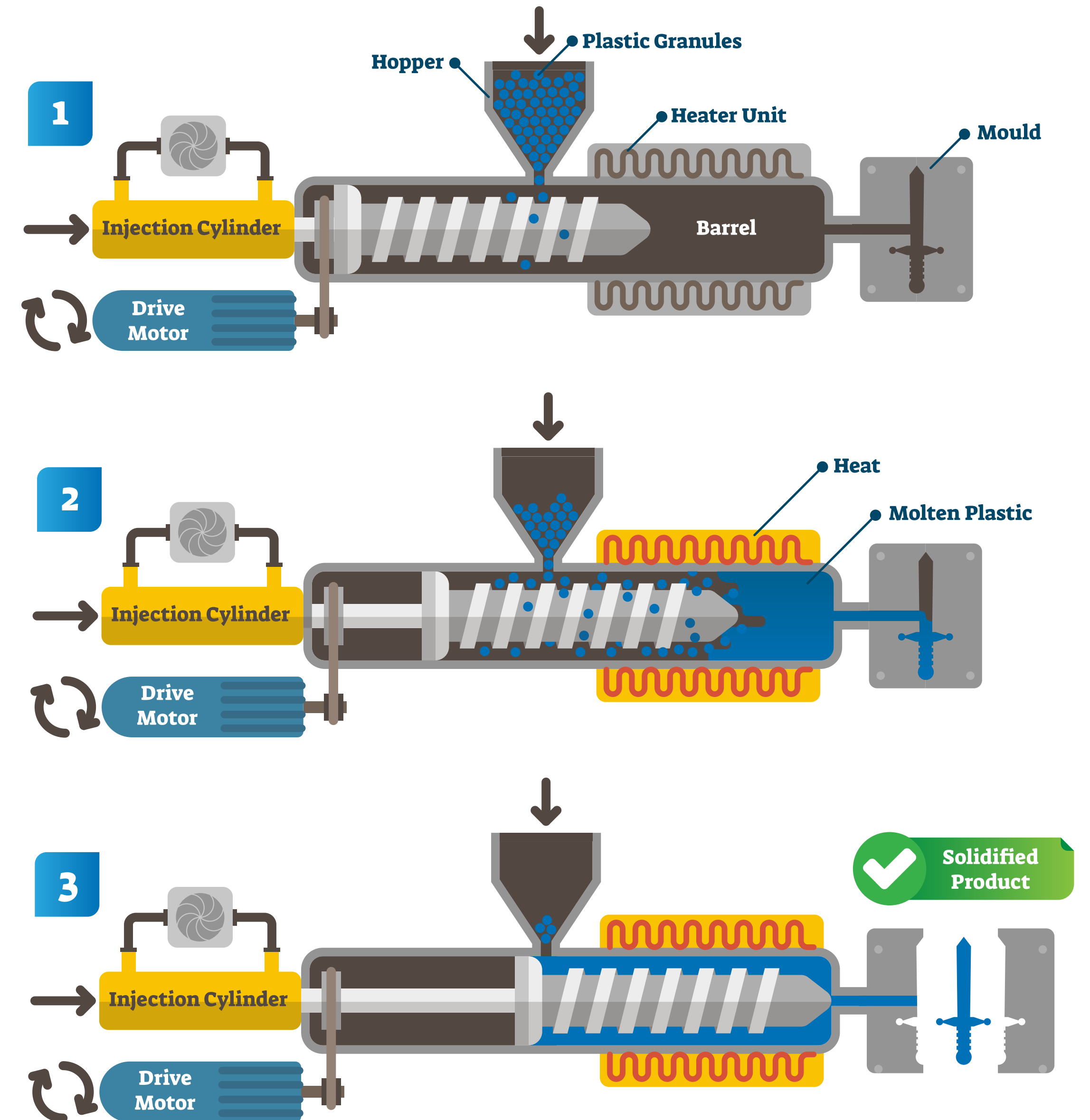


Steps of Injection Molding

injection cycle ($\ll 1$ min)



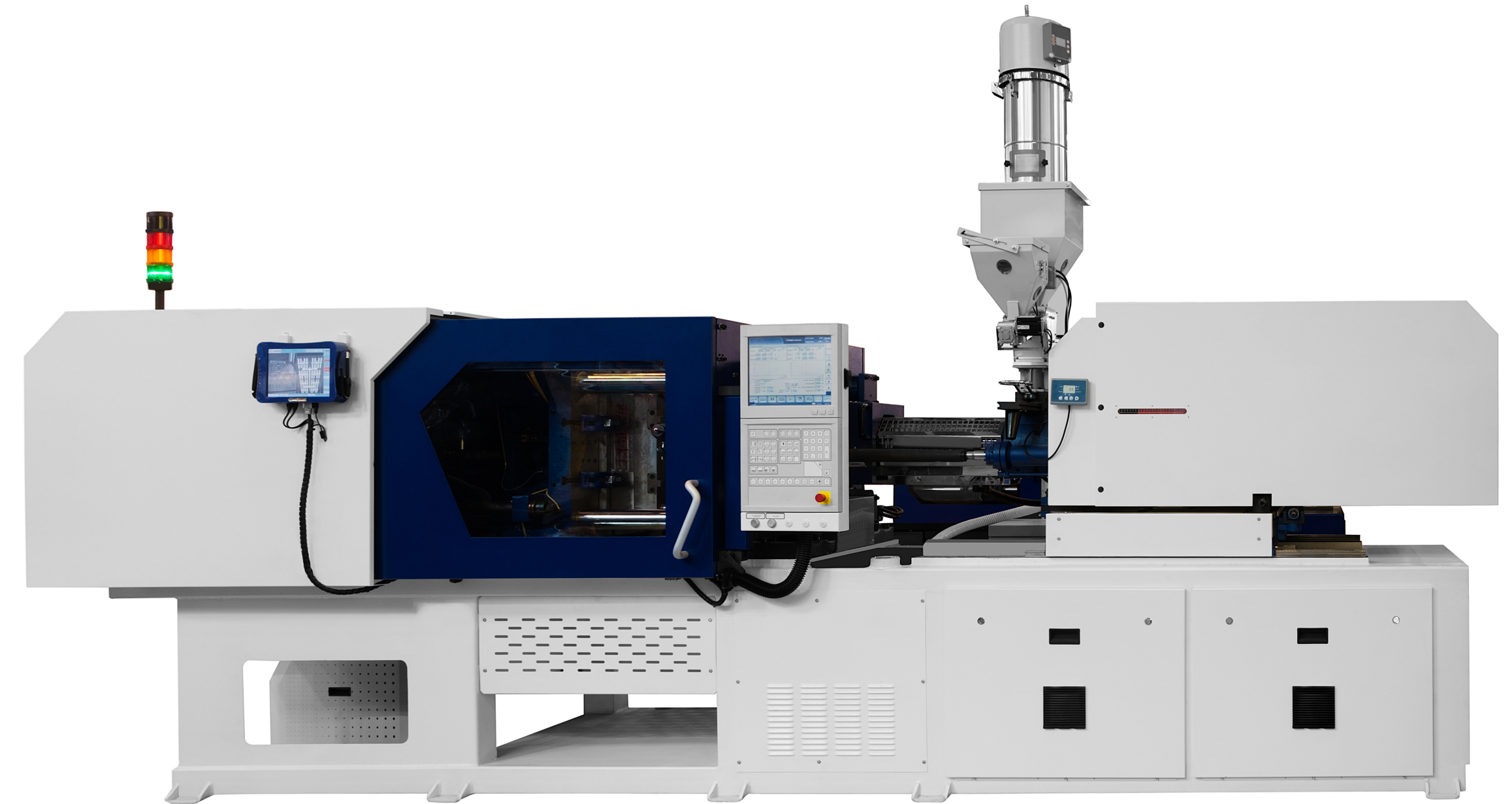
- injection molding relies on fast cycle times



important parameters

the machine

- **temperature of the extruder zone**
 - **recoil of the screw** (determines the volume of the material to be injected)
 - **rotation speed of the screw**
 - **pressure and speed of injection** (determining the filling quality of the mold)
 - **pressure and holding time for controlling the material supply** (the material contracts upon solidification)
-
- **an injection machine consists of the plasticization unit (extruder, dosing zone, outlet valve), mould, and control system for mould closing**



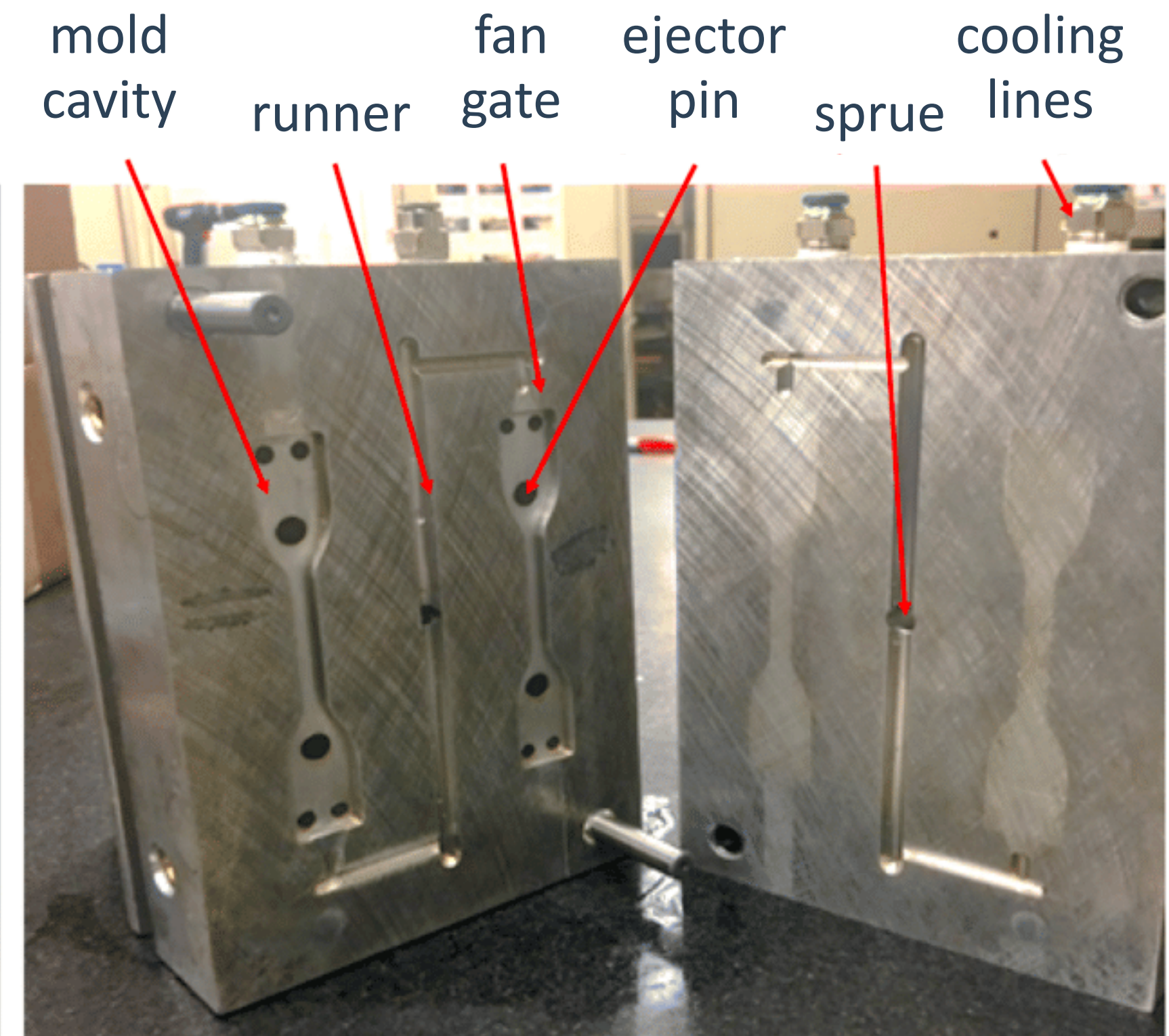
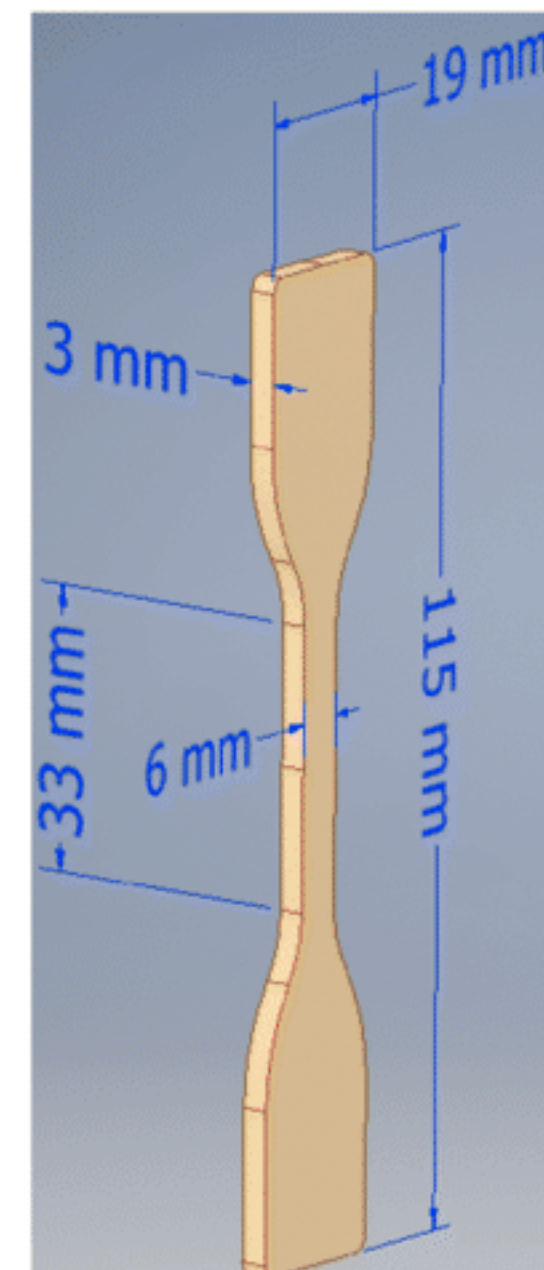
The Mould

- typically made from hardened steel, pre-hardened steel, aluminum, and/or BeCu alloy
- simple single cavity mold: 3'000–4'000 CHF (medium/complex multi cavity molds > 100'000 CHF)

product fabrication

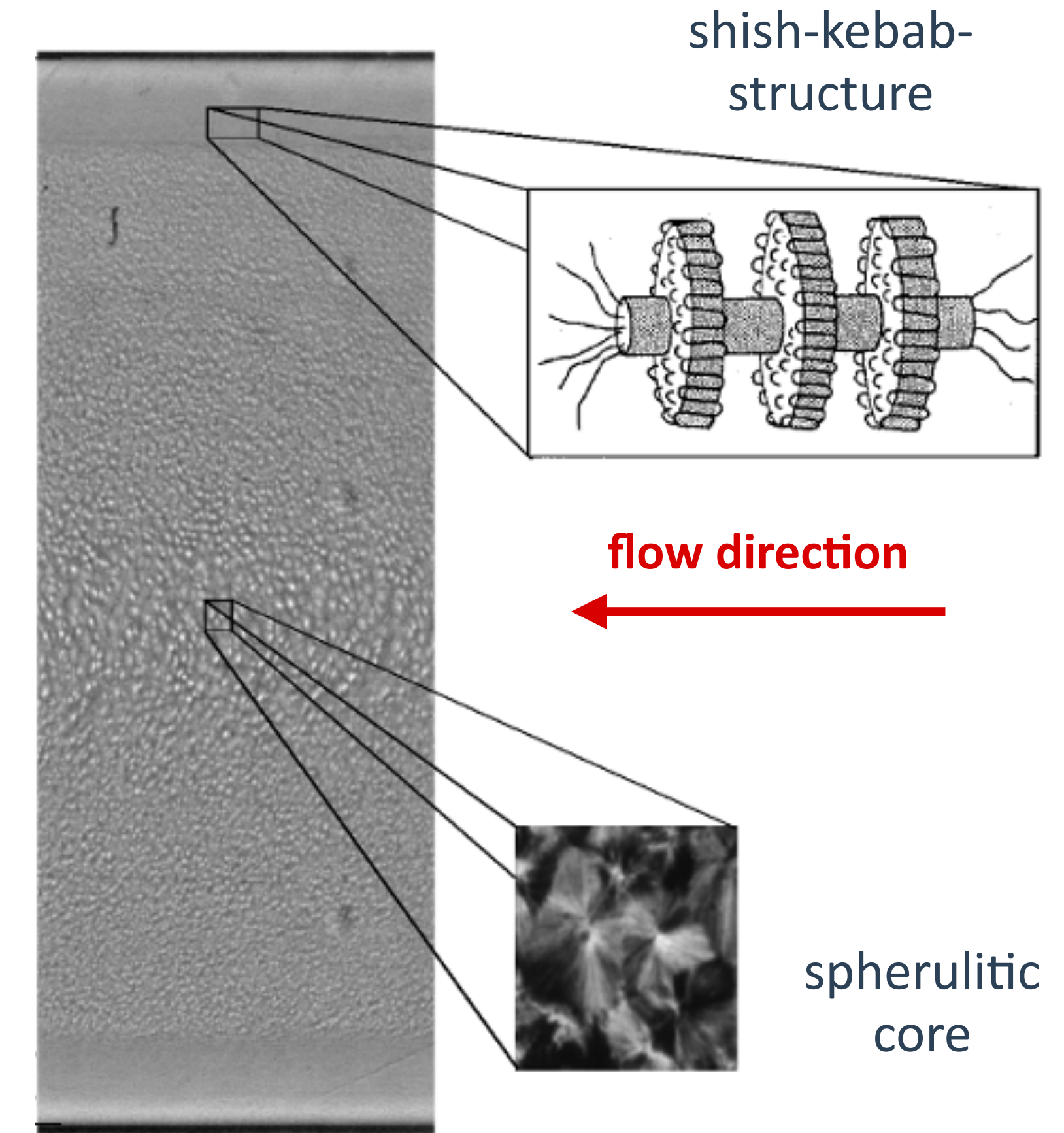
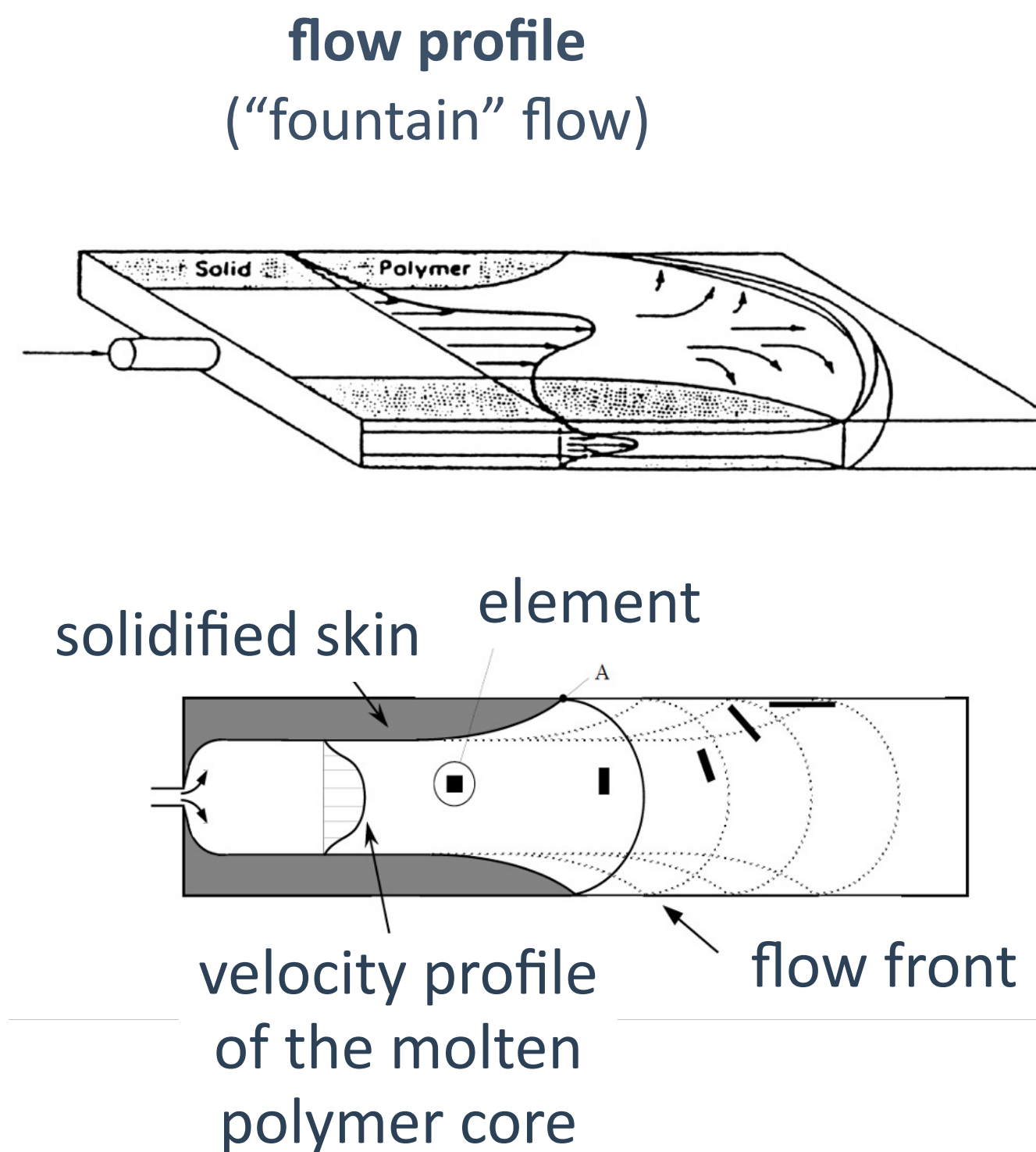
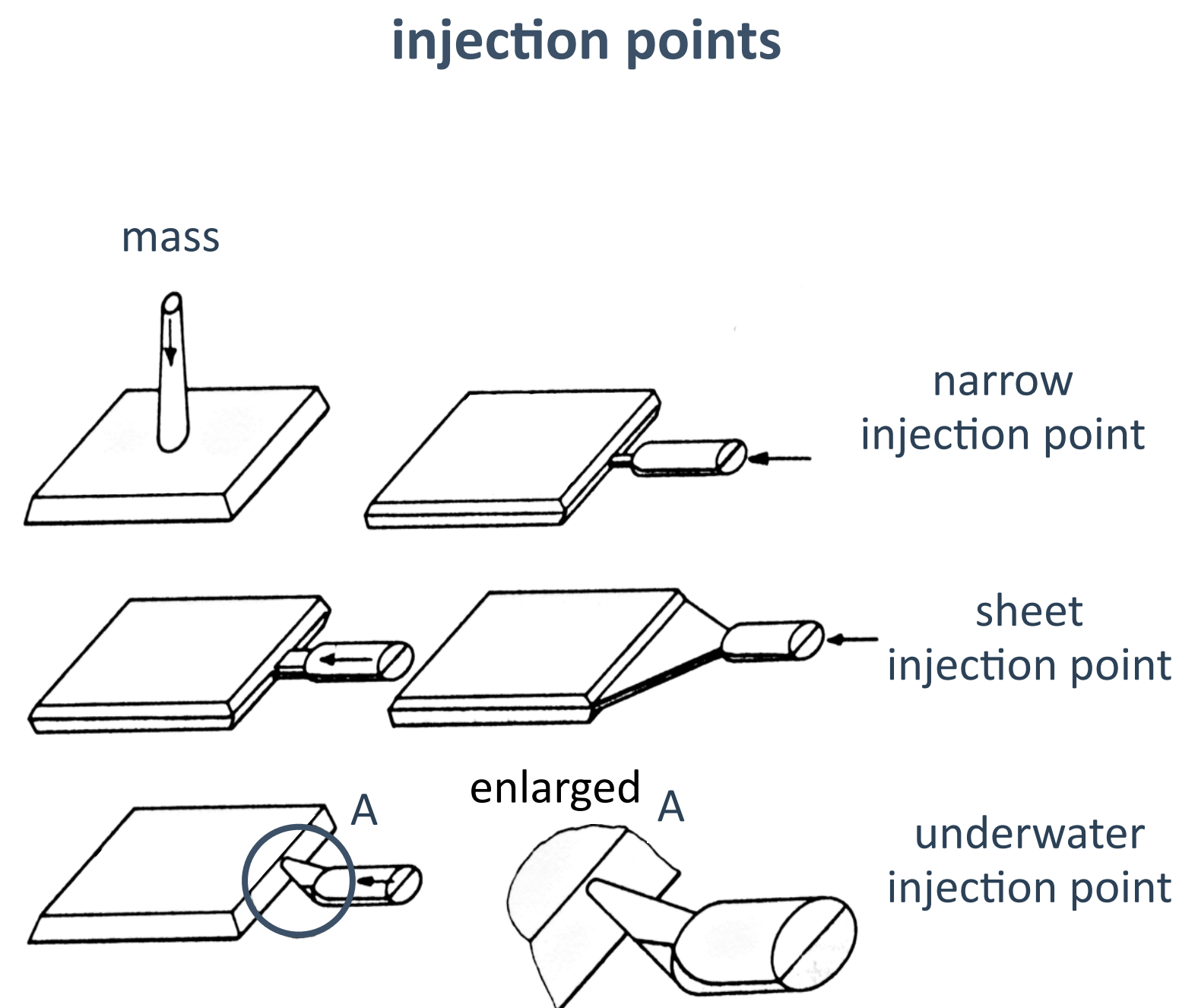


polymer testing



Filling and Solidification in the Mould

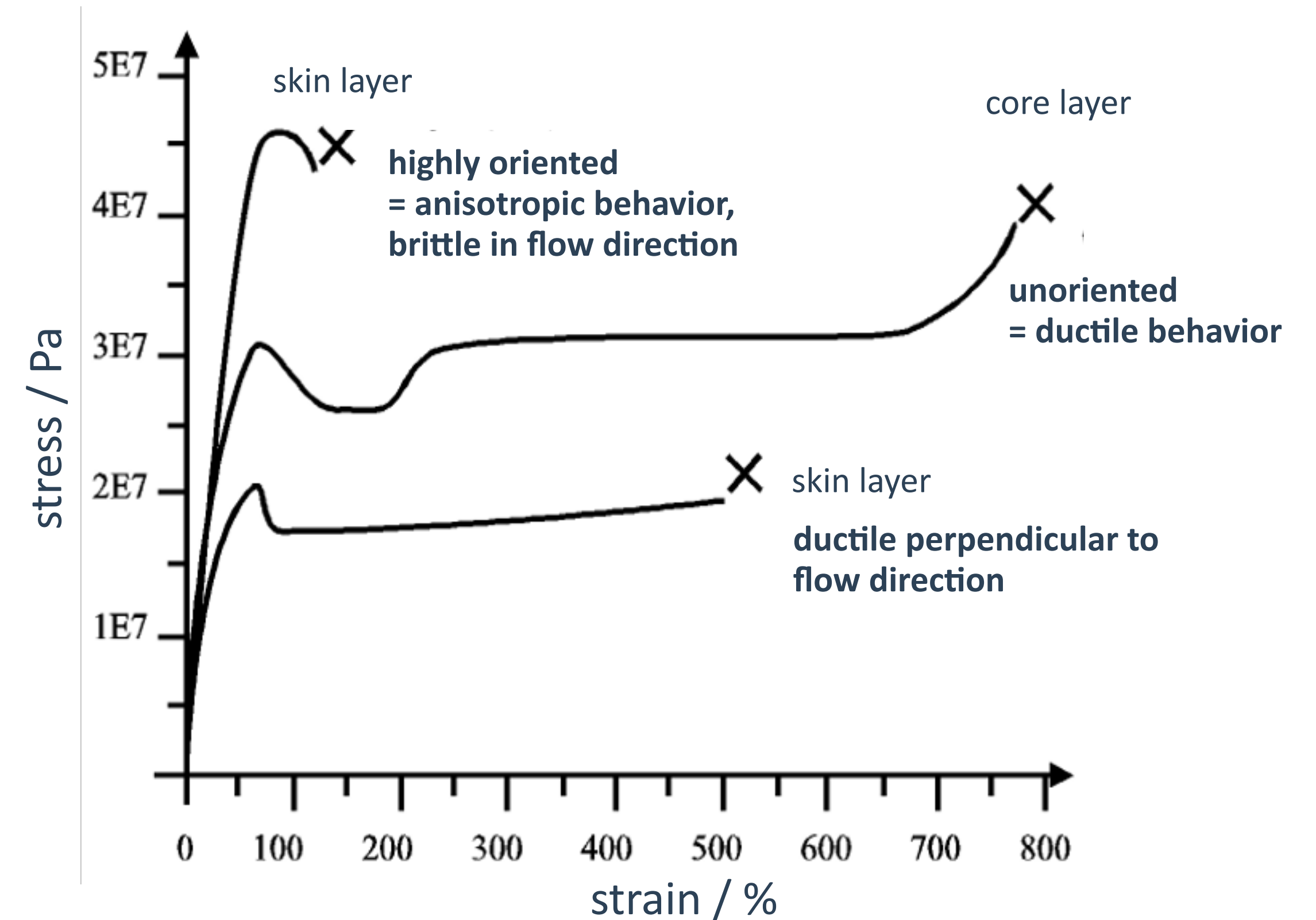
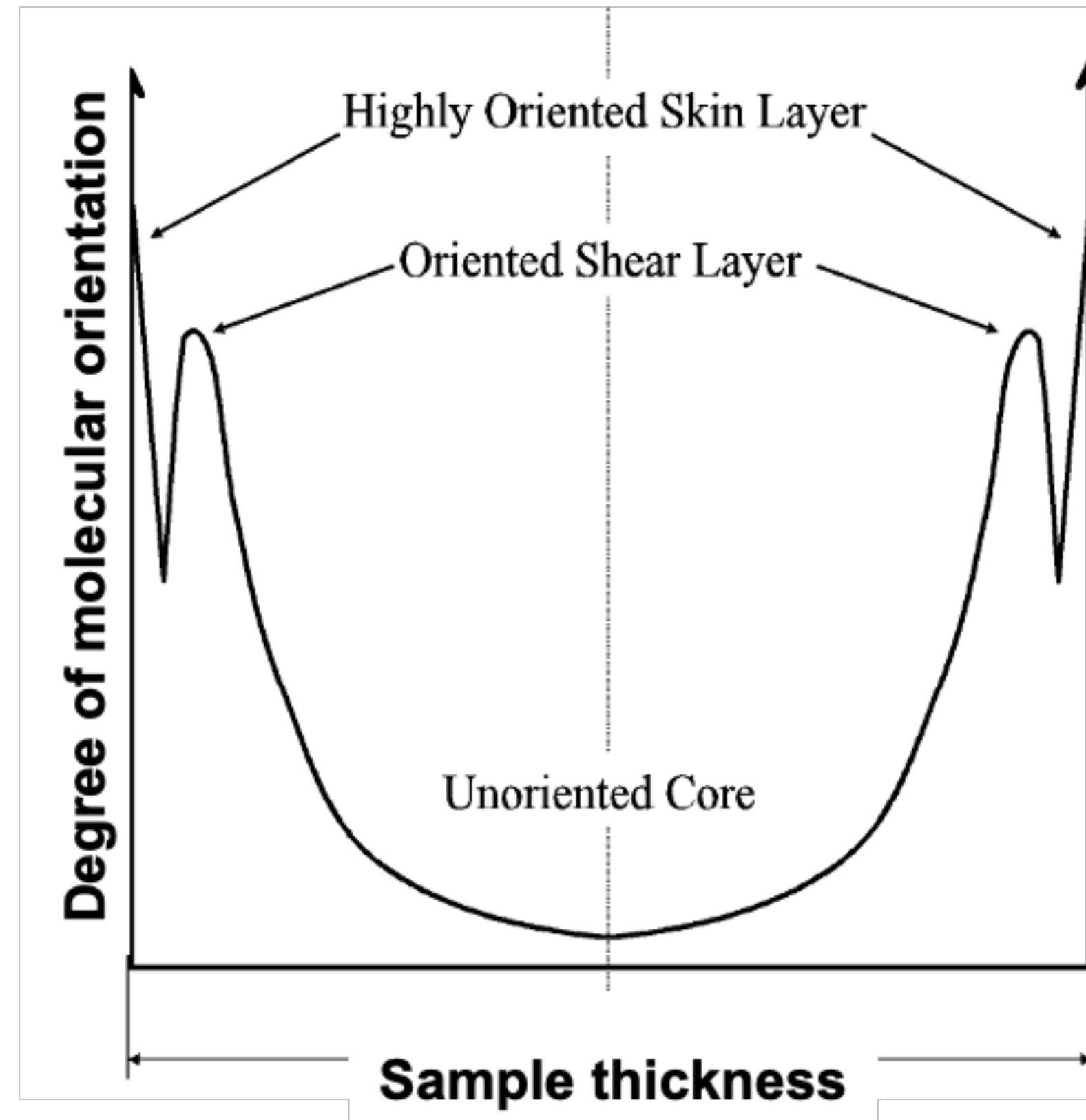
- optimised energy consumption per part requires to limit injection temperature and pressure and to increase the injection rate as much as possible



- strongly stretched chains just behind the flow front, pressed against the walls, oriented in flow direction
- without flow, we observe a spherulitic structure (see [Chapter 3.3](#))

Orientation-dependent Mechanical Behaviour

- shear stresses appear elsewhere when the flow is non-isothermal, leading of differently oriented layers

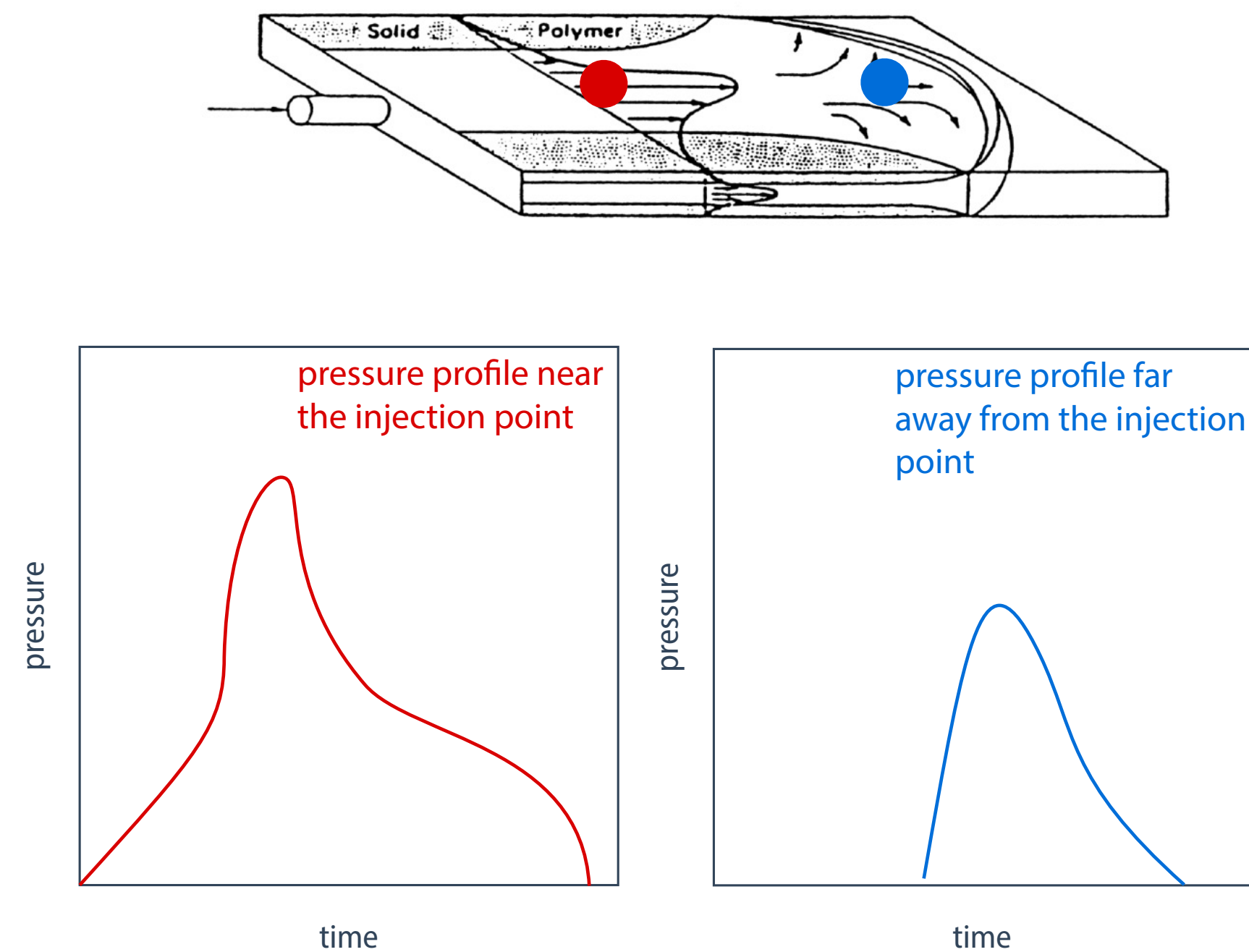


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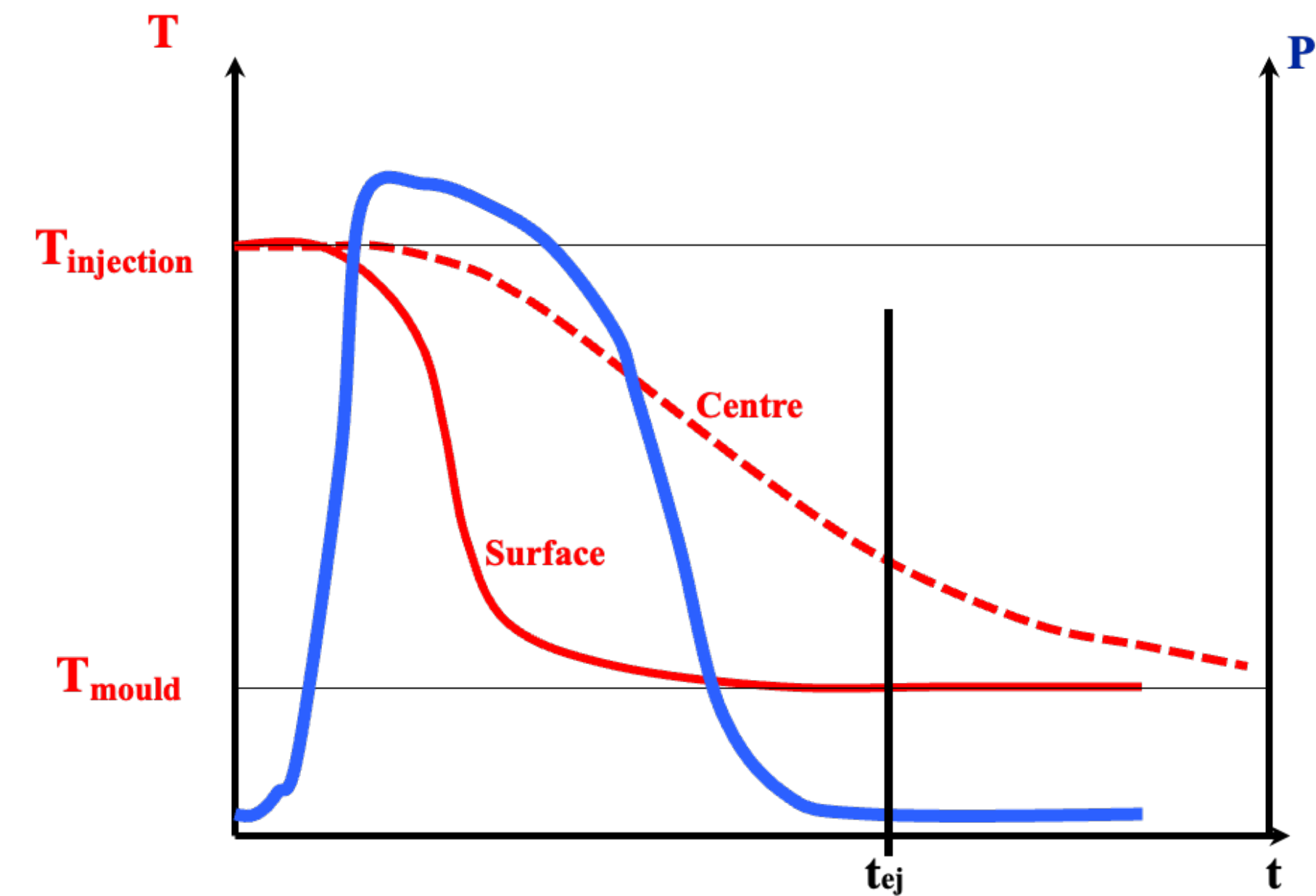
Effect of Pressure

- pressure at the mould entrance equals that induced by the piston, but deviations in parts far away from the injection point

pressure profile variations



pressure and holding time

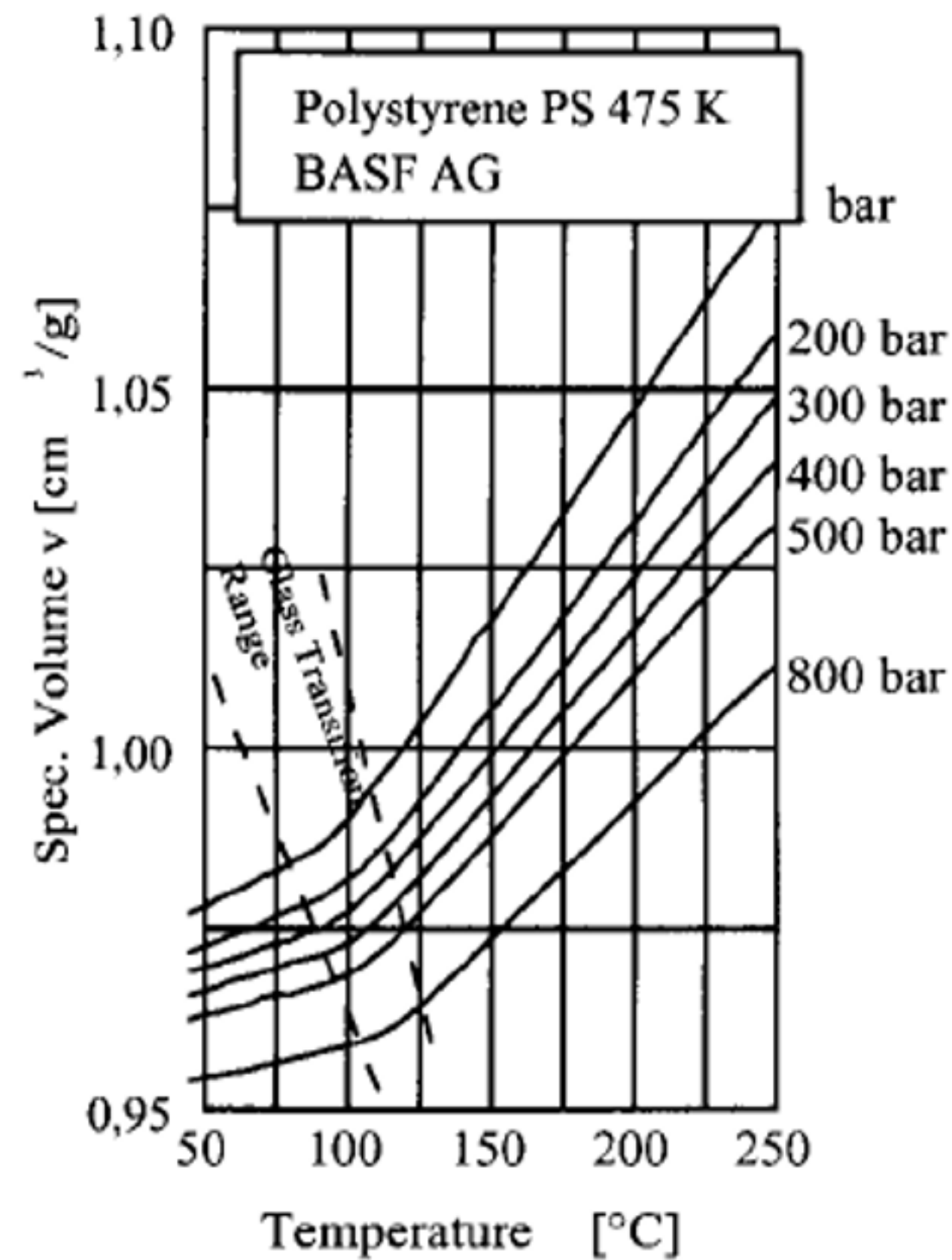


- pressure and holding time for compensation of materials shrinkage during crystallization**
(continued materials injection; dilatational expansion as the pressure diminishes)

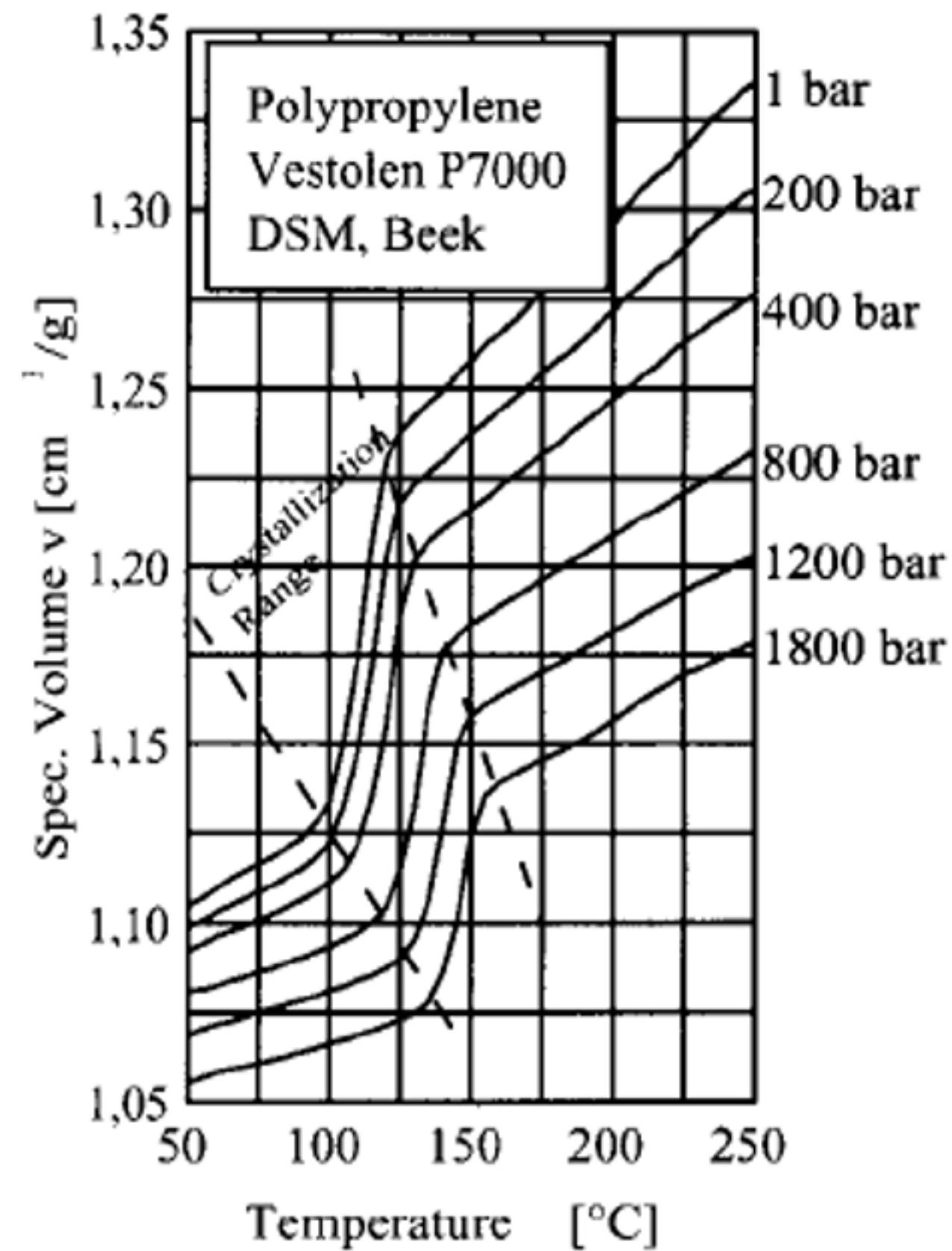
Effect of Shrinkage

- shrinkage is more pronounced in semicrystalline polymers

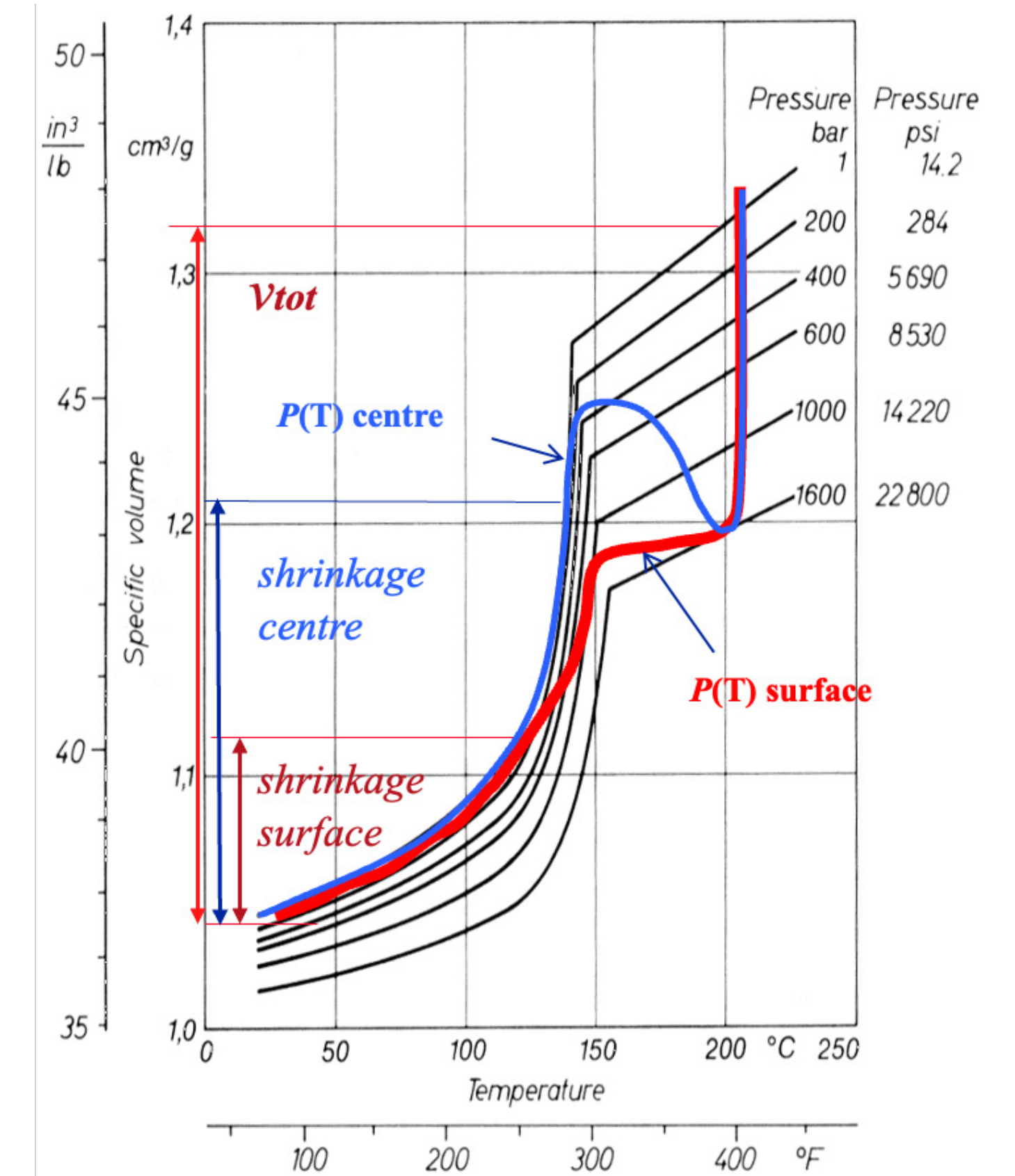
PVT diagram (amorphous)



PVT diagram (semicrystalline)



effect of maintained pressure



- it is a challenge to optimize the time at the holding pressure for the entire piece

Design

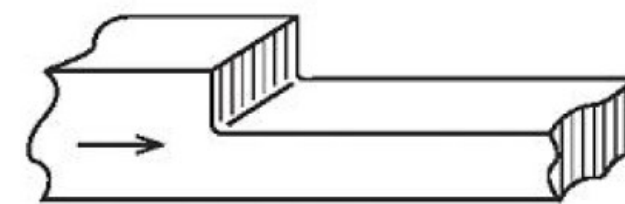
- the mould is expensive and must be get right already at the first try (simulation tools exist!)

part design

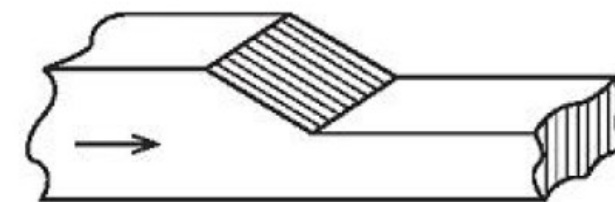
- mechanical behavior** (stiffness, impact)
- thermal behavior** (stiffness, creep)
- chemical resistance** (material selection)
- cosmetics** (surface finish, color, gate location, ribs, weld line)
- mouldability** (wall thickness, flow length, gating ...)
- assembly** (screws, welding , bonding...)
- painting**

mould design

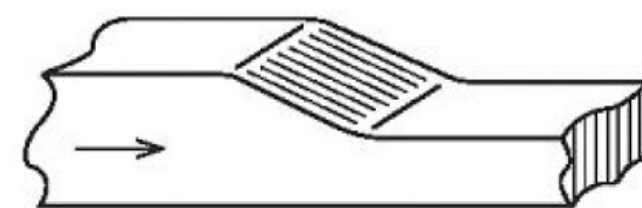
Wall section transition



Sharp - not recommended

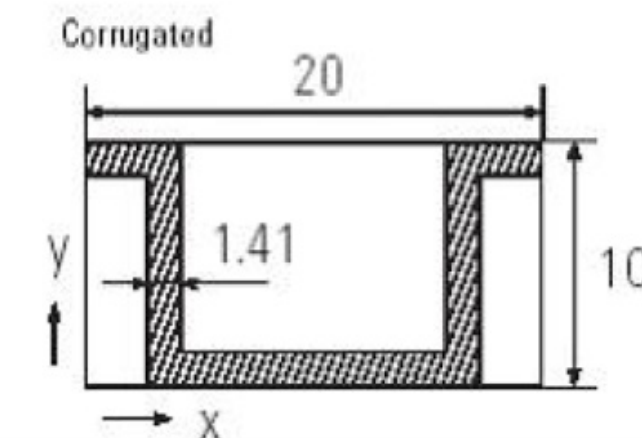
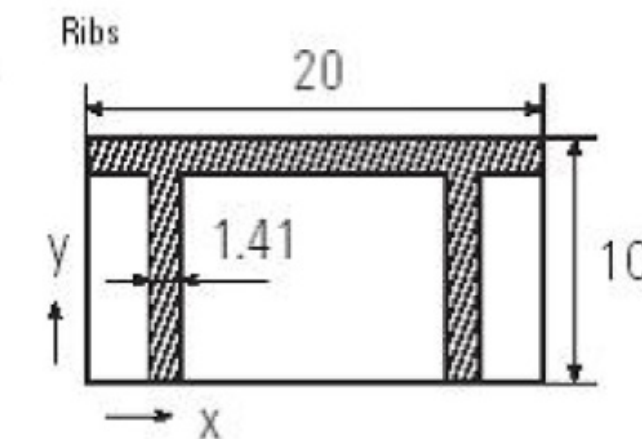
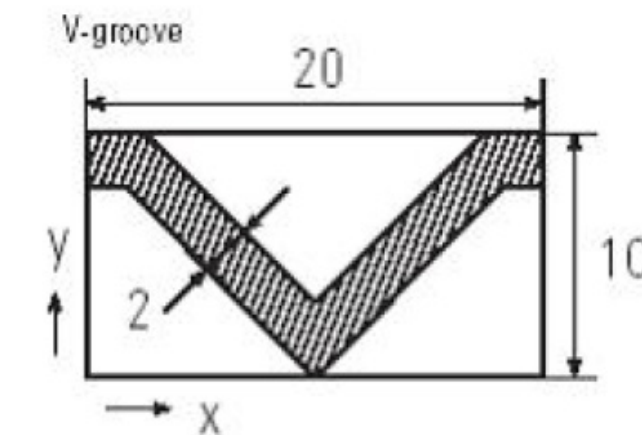


Tapered - better



Gradual - recommended

design for stiffness

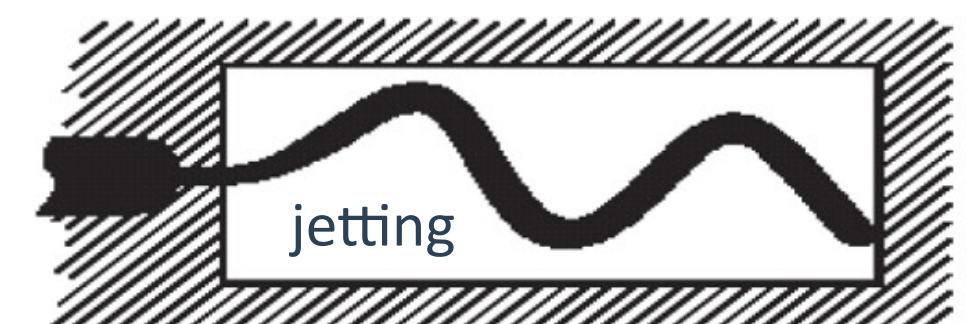


design for appearance

Side view



Top view



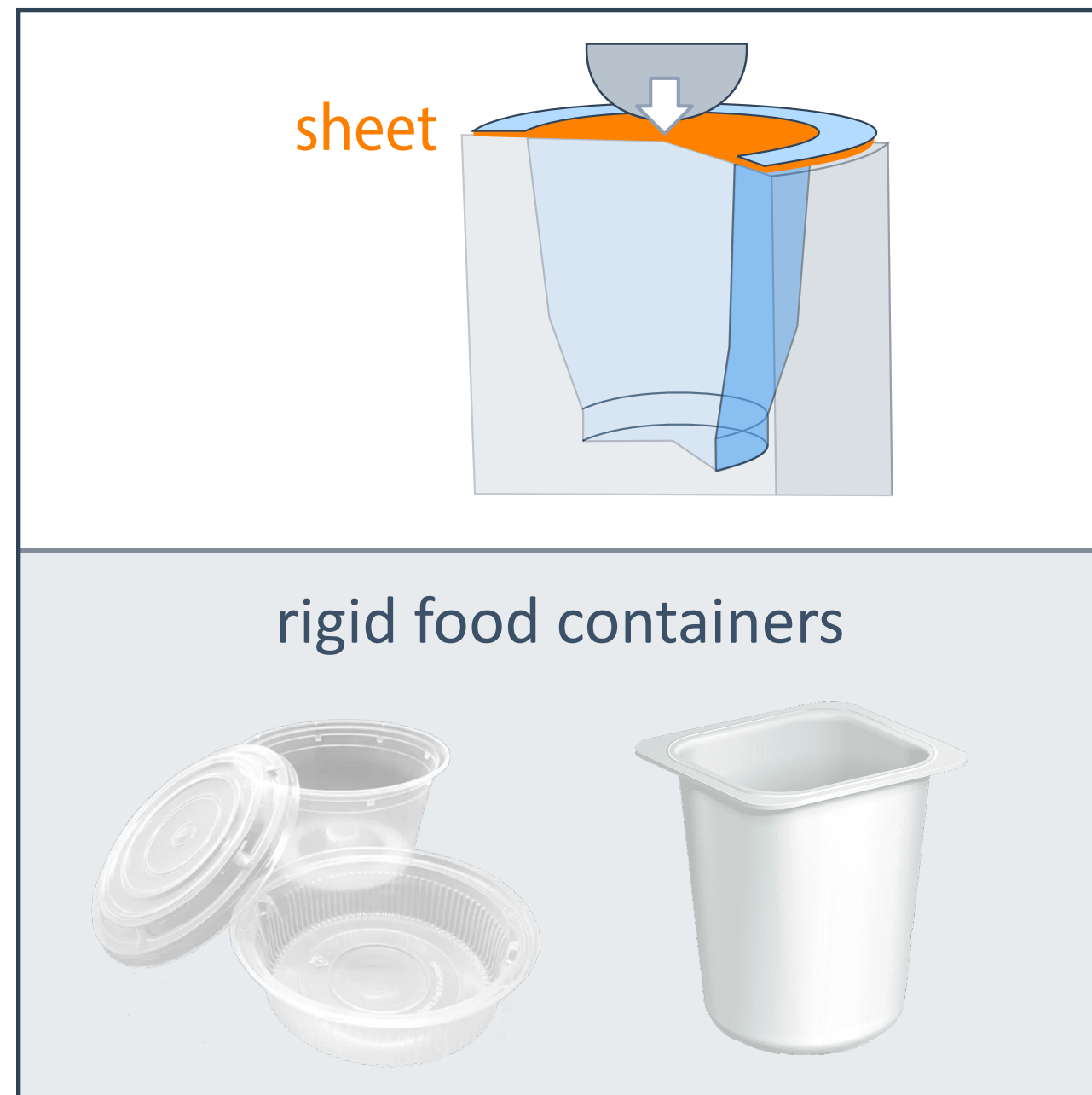
- design for mouldability, stiffness, impact, appearance, precision**

Other Processing Techniques

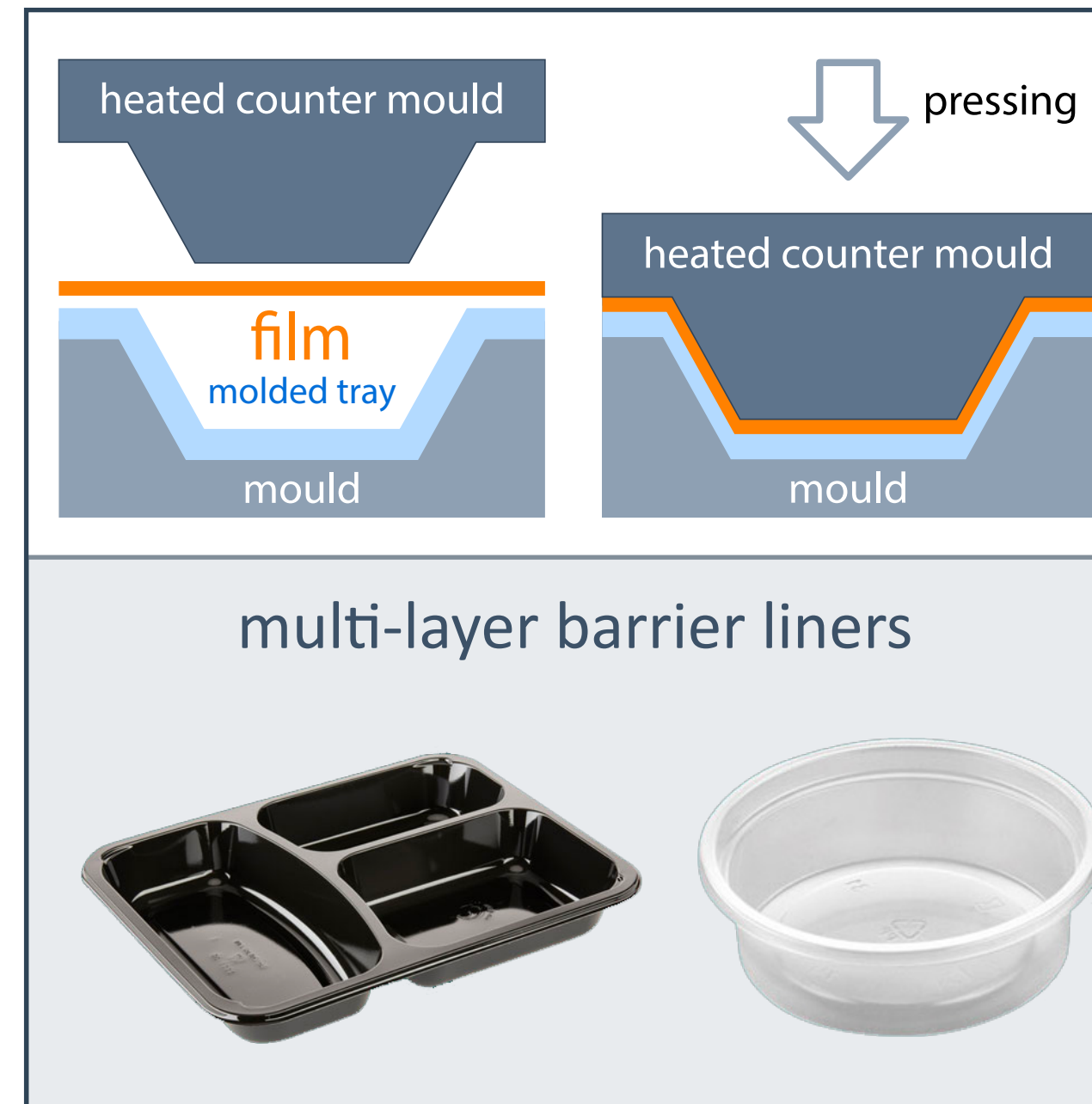
Thermoforming

- shaping of thermoplastic sheets (e.g. calendared) by the action of vacuum, pressure, and an imprint
- process usually carried out from the **rubbery state** (well suited technique for amorphous polymers)

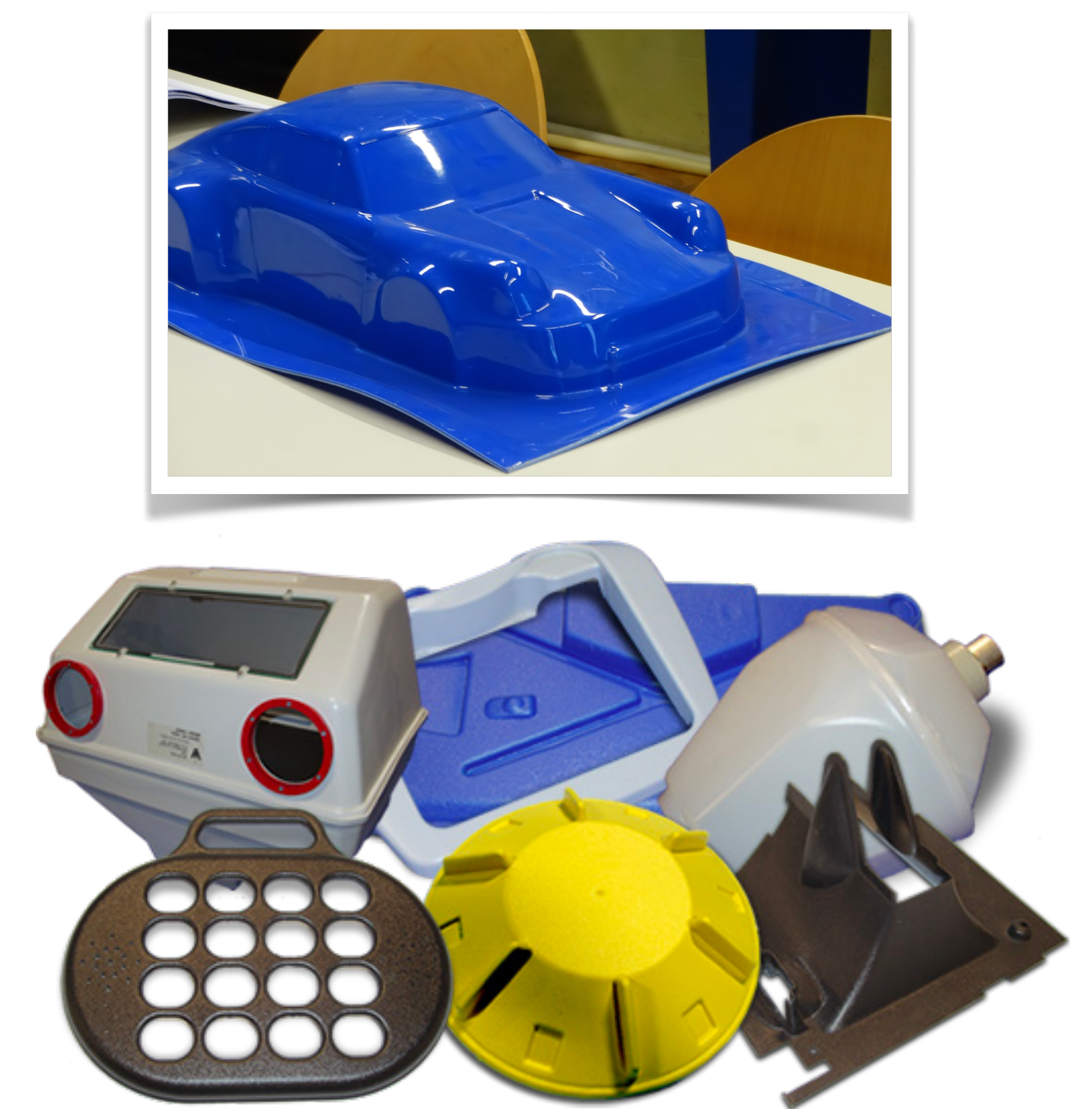
3D thermoforming



thermo-lamination



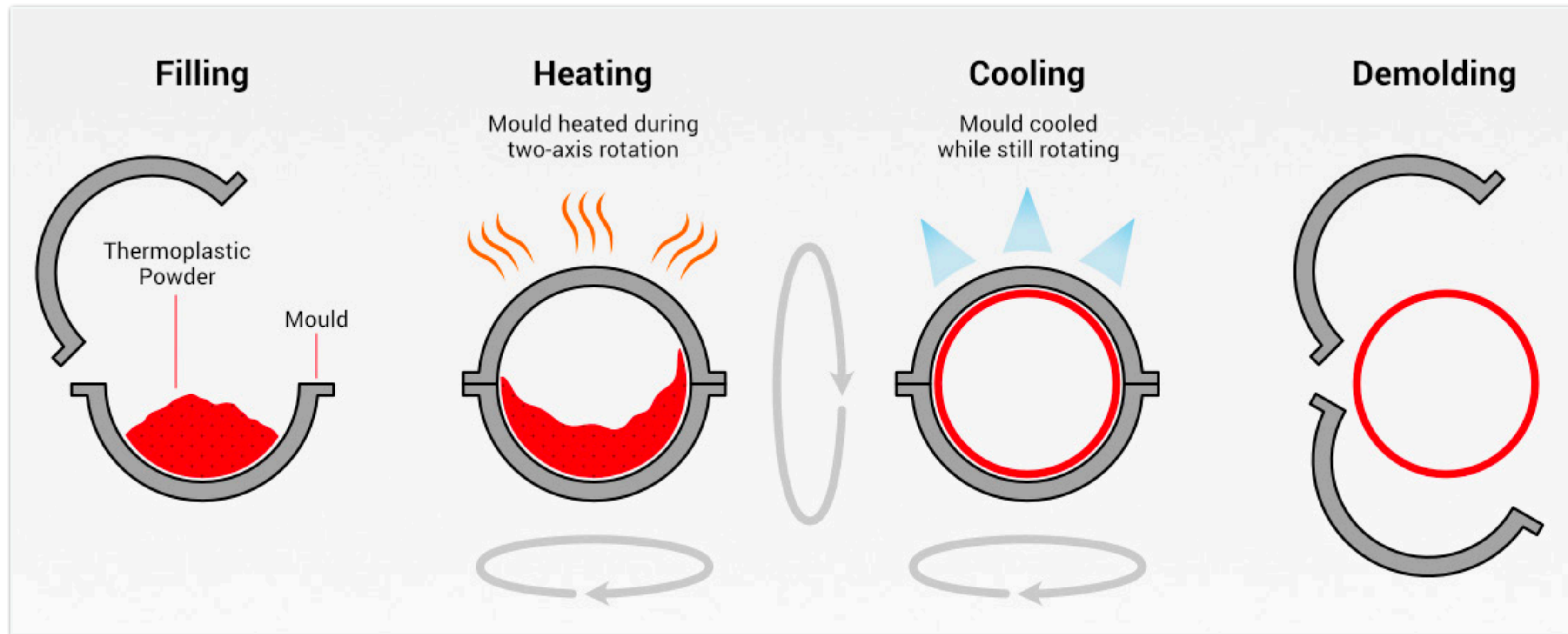
thermoformed products



- **mass production of small and light parts with high precision** (also used for multi-layer sheets and others...)

Rotational Moulding

- **for closed hollow objects** produced in a heated mould that can be rotated around two orthogonal axes:

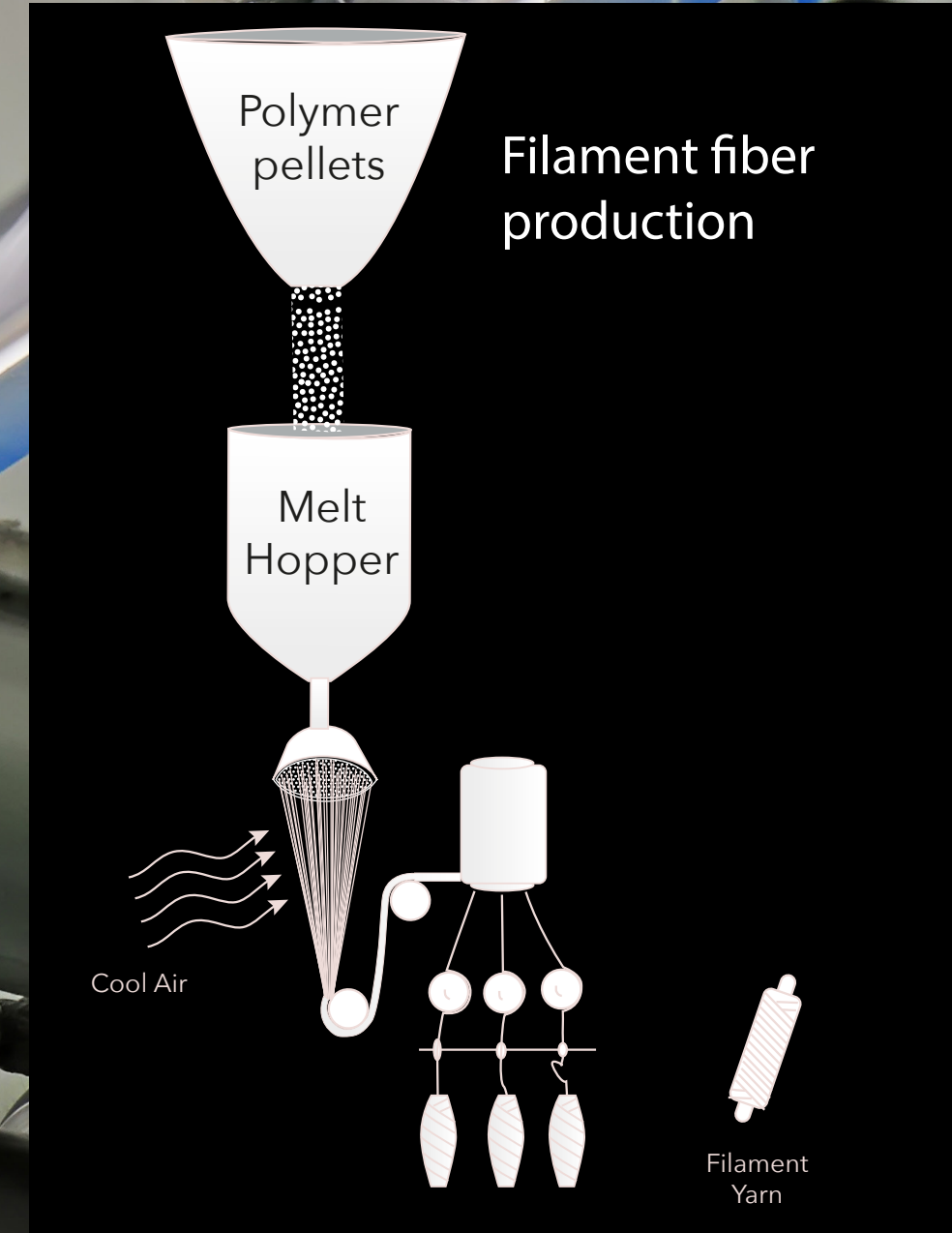


- **pro:** lightweight & inexpensive moulds, large and complex product dimensions possible, no welding, regular thickness, option for several layers of different colors, compliant with glass fibre reinforcement
- **contra:** limited accuracy & materials choice, thick walls needed, materials loss at the opening of ca. 10%

Calendering

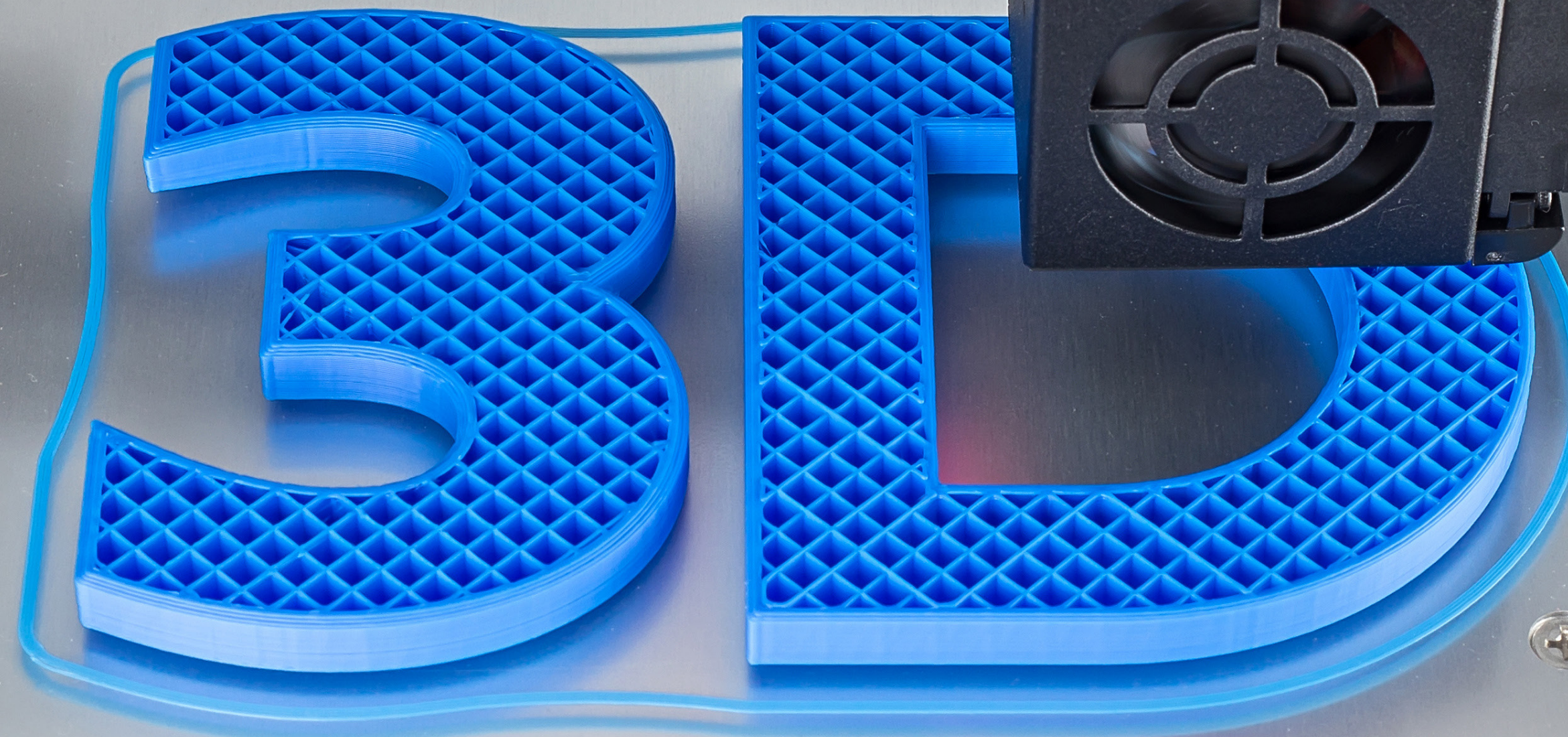
- **calendering:** lower formulation cost, higher flow (up to 5'000 kg/h), accurate thickness (error 2-3%), waste generation (1%), thickness range ($> 50 \mu\text{m}$), **but 4-times more expensive purchase & maintenance costs**
- **extrusion:** higher formulation cost (antioxidants), max flow only up to 500 kg/h, thickness variation 5–10%, waste generation (10%), sheet thickness 5–50 mm

Fiber Spinning



- requires high melt elasticity and strain-at-break above the solidification temperature
- winding speed determines degree of orientation, morphology, and hence mechanical performance
- important for various synthetic fibers: LDPE, HDPE, UHWMPE, iPP, nylons, polyester, polyurethanes...

3D Printing



- **very accessible & emerging technology** (almost same price as traditional printers) **for very complex shapes**
- **possibility of incorporating different materials** (e.g. reinforcing fibers)
- **enormous potential for miniaturization** as well as for biological systems (“printed” organs)

written exam

Wednesday, January 22, 9¹⁵ – 12¹⁵

CE1101

up to 12 multiple-choice questions (only one answer is correct)

1. Which of the following reactions is a polycondensation?

a) Reaction of an epoxy resin with a diamine in a closed mold.

b) Reaction of a diisocyanate with a diol in the presence of water to form a foamed polyurethane.

c) Ring opening polymerization of caprolactam to form polyamide 6.

d) Radical polymerization of ethylene to form polyethylene.
2. For an amorphous polymer of high molar mass, $C_{\infty} = 9$ and the maximum deformability of the entanglement network, $\lambda_{\max} = 4$. What is the average number of bonds between two entanglement points?

a) 20

b) 36

c) 81

d) 144

4 out of 6 longer questions need to be answered

1. The melting temperature of a crystalline lamella formed by a polymer is given by

$$T_m = T_{m0} \left(1 - \frac{2\sigma_e}{l\Delta H} \right)$$

- a) Explain the meaning of the different terms in this equation with reference to a schematic representation of a lamella, and thus explain its physical origin.
- b) In a semi-crystalline polymer, the lamellae are organized in the form of spherulites. What is a spherulite and what are the mechanisms that lead to the formation of spherulites from lamellar nuclei within a molten polymer when $T_g < T < T_{mo}$?
- c) During injection molding, a highly stretched molten polymer comes into contact with the walls of a cold mold. What are the consequences for its morphology? (Assuming that the polymer is able to crystallize.)

