Injection Molding

2.810

T. Gutowski

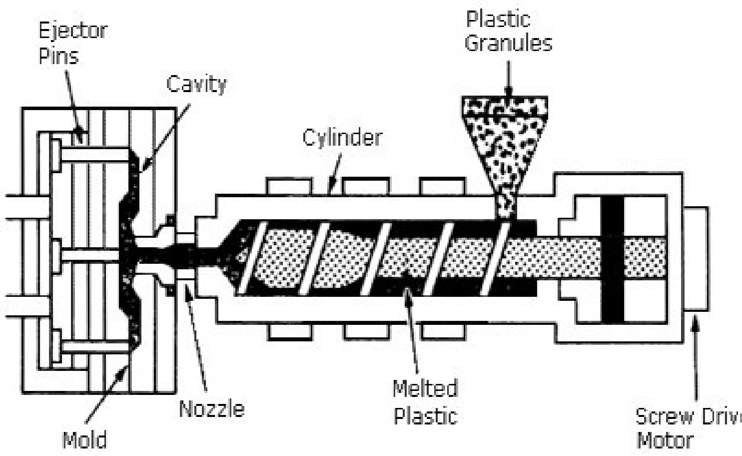


Diagram of a typical injection molding process. (Image taken from the OSHA Technical Manual.)

D. Roylance

Short history of plastics

1862 first synthetic plastic
1866 Celluloid
1891 Rayon
1907 Bakelite
1913 Cellophane
1926 PVC
1933 Polyethylene
1938 Teflon
1939 Nylon stockings
1957 velcro
1967 “The Graduate”

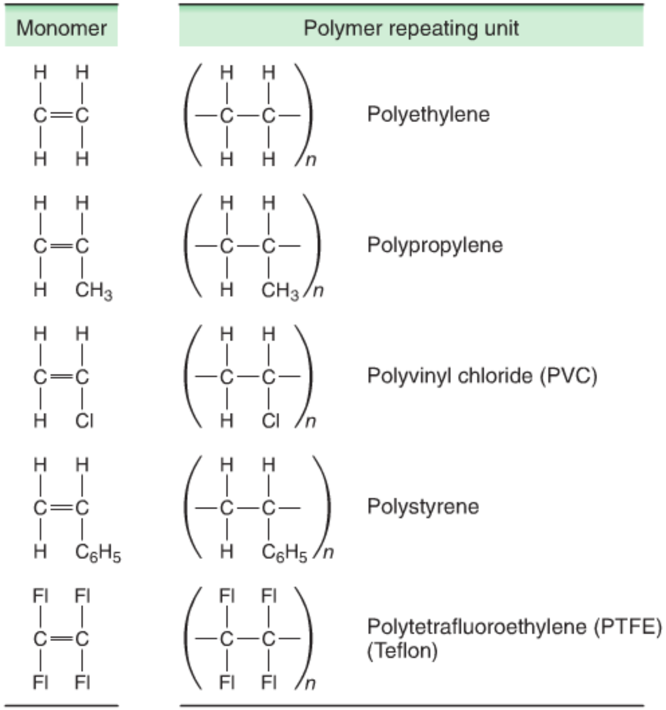


FIGURE 7.2 Molecular structure of various polymers. These are examples of the basic building blocks for plastics.

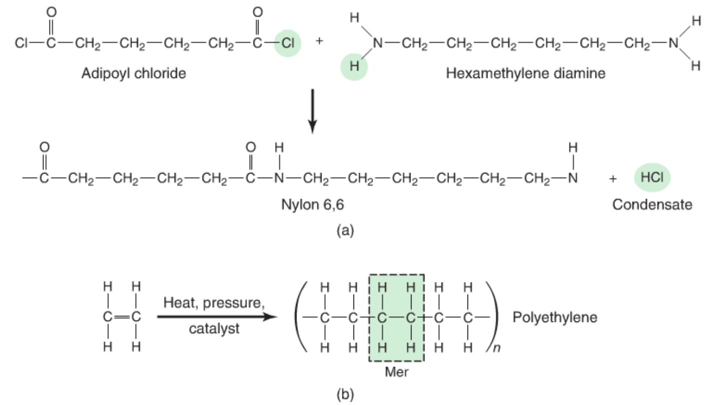


FIGURE 7.3 Examples of polymerization. (a) Condensation polymerization of nylon 6,6 and (b) addition polymerization of polyethylene molecules from ethylene mers.

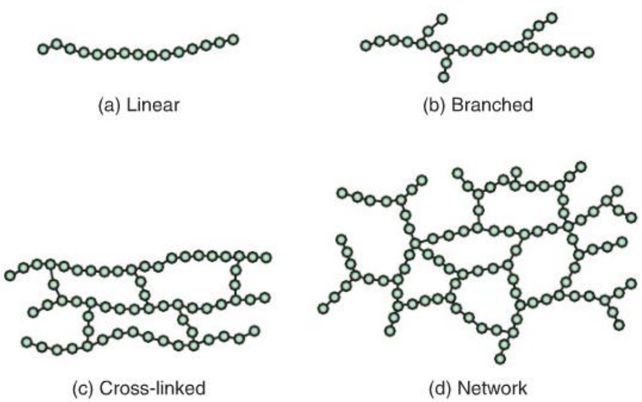
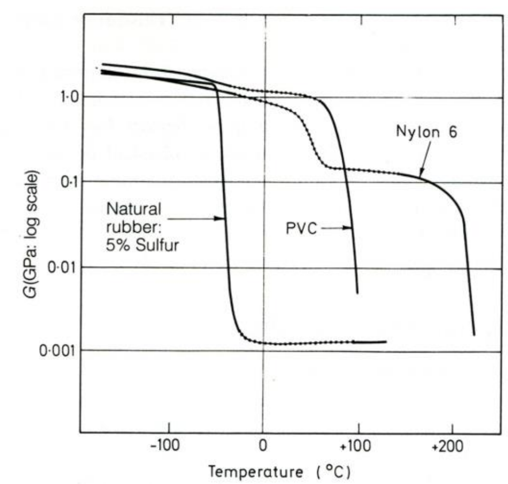


TABLE 7.2

Glass-transition and Melting Temperatures of Some Polymers

Material	T_g (°C)	T_m (°C)
Nylon 6,6	57	265
Polycarbonate	150	265
Polyester	73	265
Polyethylene		
High density	−90	137
Low density	−110	115
Polymethylmethacrylate	105	—
Polypropylene	−14	176
Polystyrene	100	239
Polytetrafluoroethylene	−90	327
Polyvinyl chloride	87	212
Rubber	−73	—



4.21 Dependence of the shear modulus on temperature for three representative engineering polymers: natural rubber (cross-linked); PVC (essentially amorphous and not cross-linked); and nylon 6 (crystalline). The temperatures at which these polymers are used in technology are indicated (•–•–•–•–•) (after Wolf).

Ref Kalpakjian and Schmid

McCrum, Buckley, Buckknall

Outline

- Basic operation
- Cycle time and heat transfer
- Flow and solidification
- Part design
- Tooling
- New developments
- Environment

30 ton, 1.5 oz (45 cm3) Engel

Injection Molding Machine
for wheel fabrication

Process & machine schematics

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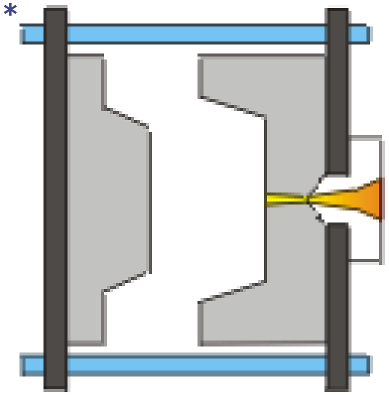

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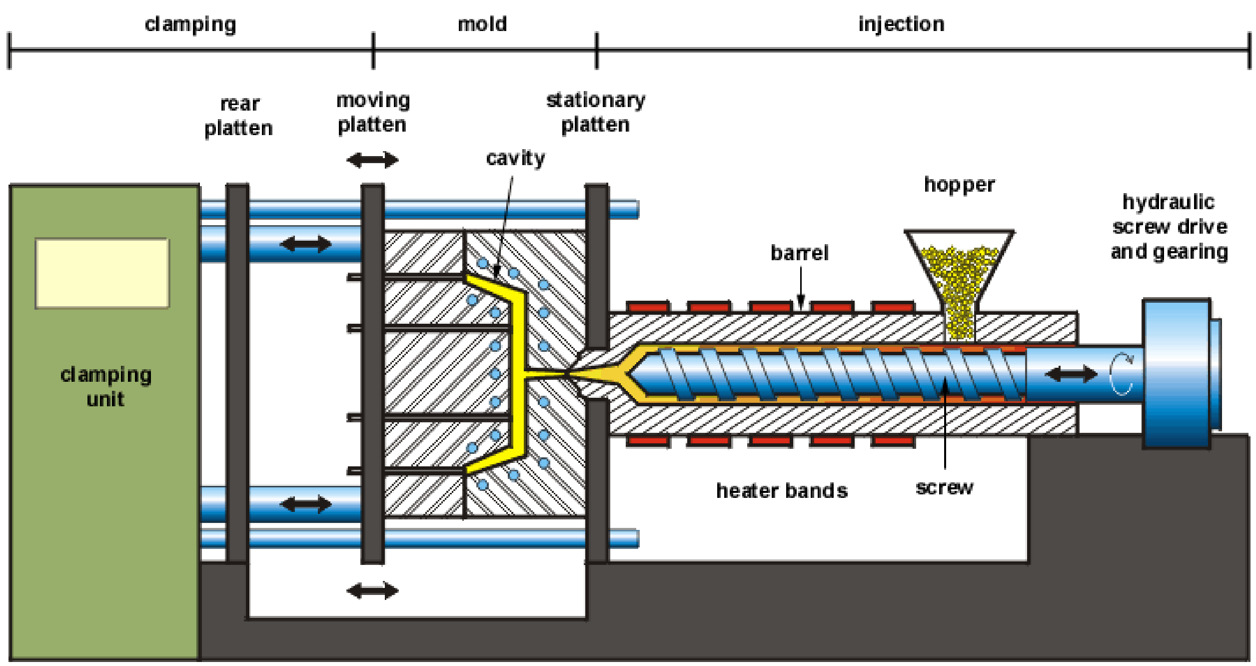
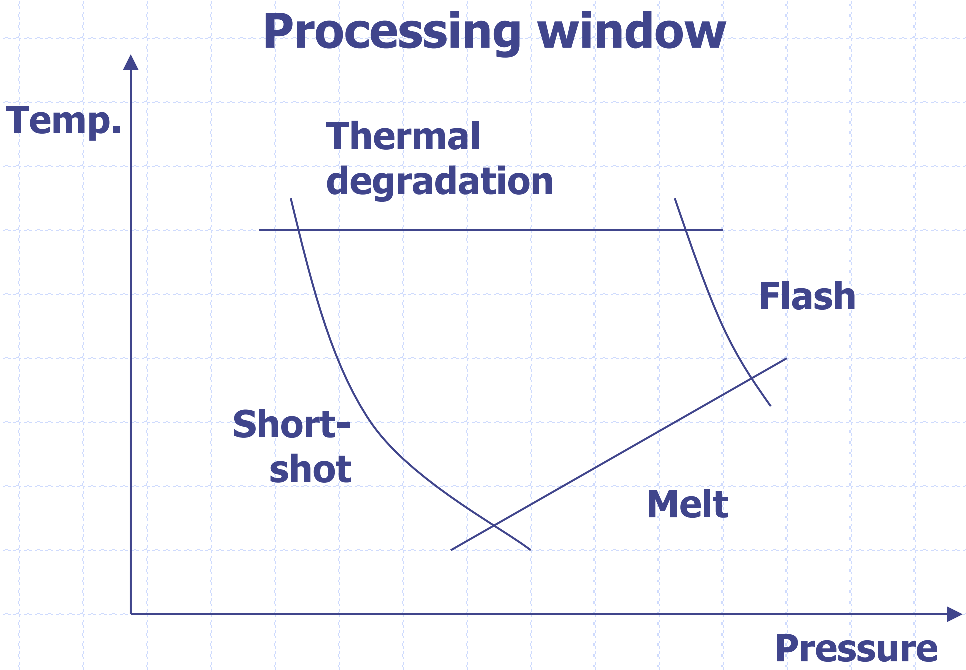


Schematic of thermoplastic Injection molding machine

* Source: http://www.idsa-mp.org/proc/plastic/injection/injection_process.htm

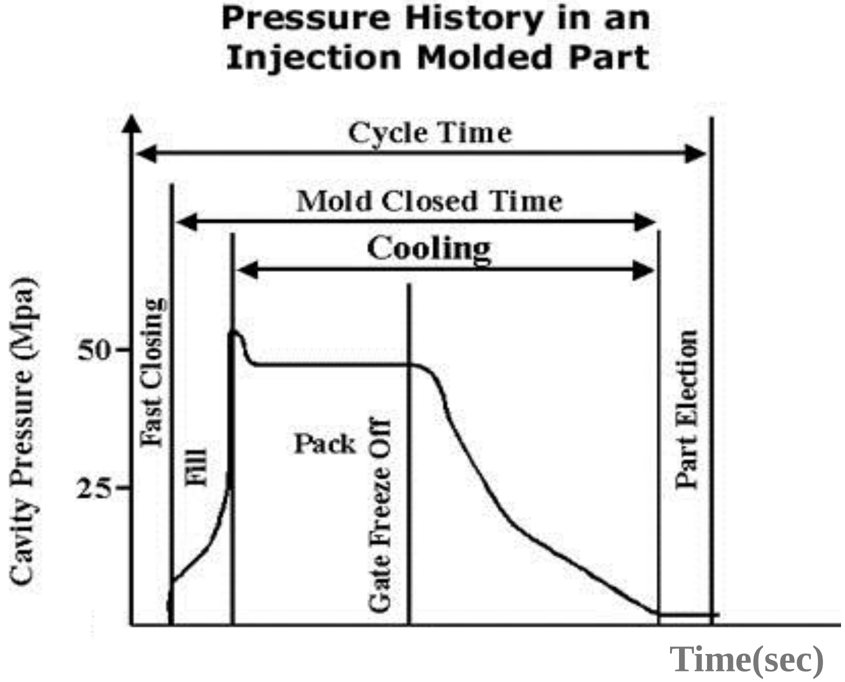
Process Operation

- Temperature: barrel zones, tool, die zone
- Pressures: injection max, hold
- Times: injection, hold, tool opening
- Shot size: screw travel



Typical pressure/temperature cycle

*



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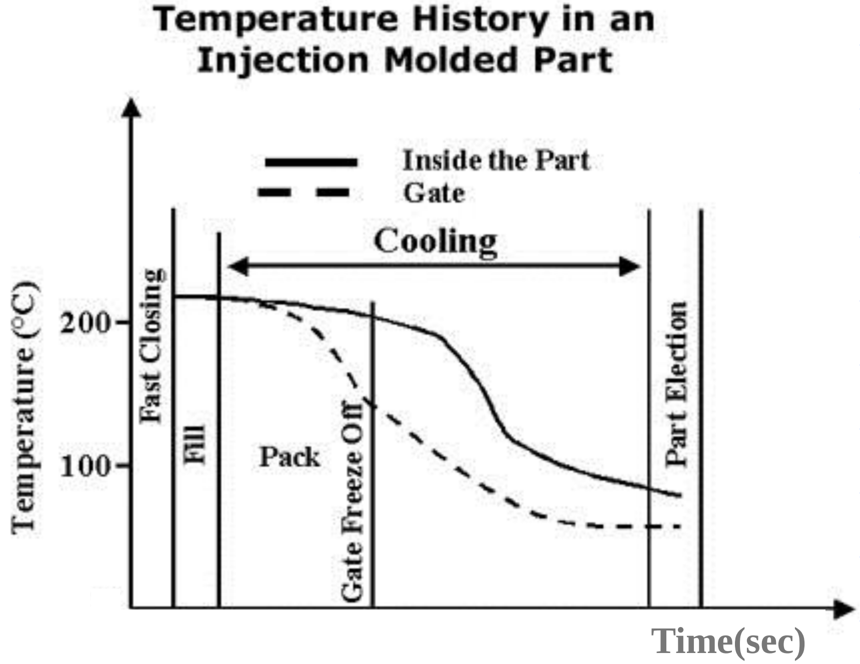


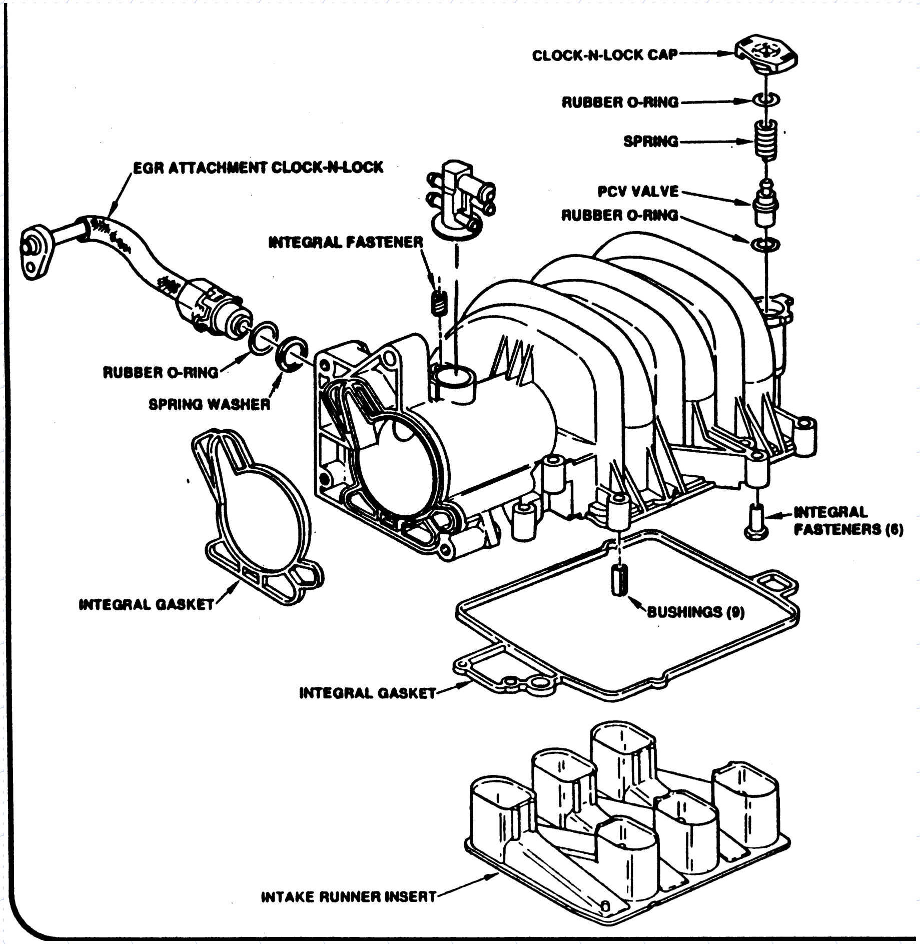
Cooling time generally dominates cycle time

$$t_{cool} = \frac{(\text{half thickness})^2}{\alpha}$$

$$\alpha = 10^{-3}\, cm^2/\sec \text{ for polymers}$$

* Source: http://islnotes.cps.msu.edu/trp/inj/inj_time.html

Calculate clamp force, & shot size



F=P X A = 420 tons

3.8 lbs = 2245 cm^3

=75 oz

Actual ; 2 cavity 800 ton

Clamp force and machine cost

Design for Injection Molding 351

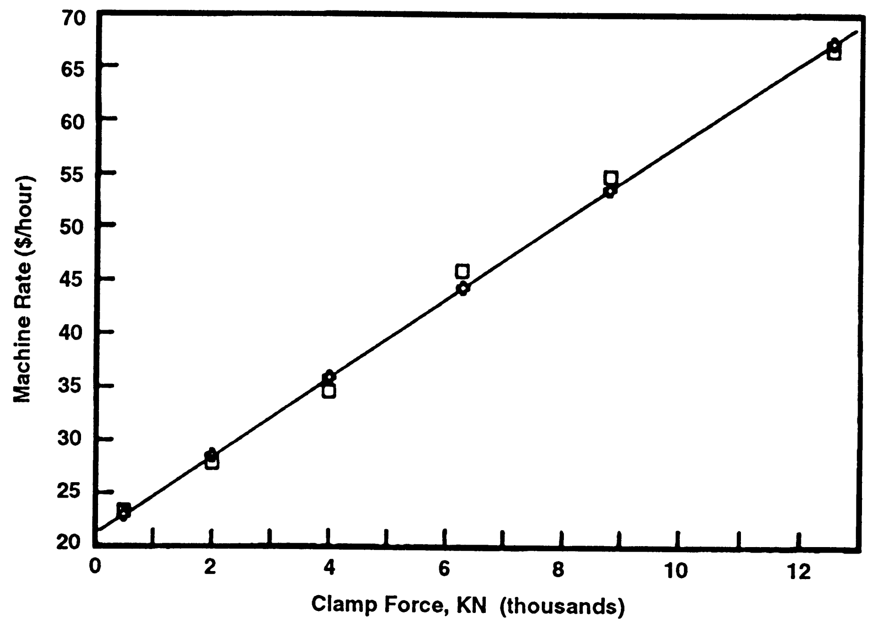
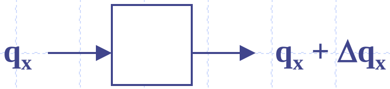


Figure 8.9 National average injection molding machine rates.

Heat transfer Note; $\alpha_{Tool} \geq \alpha_{polymer}$

1-dimensional heat conduction equation :



$$\frac{\partial}{\partial t}(\rho \cdot c \cdot T)\Delta x \Delta y = -\frac{\partial q_x}{\partial x}\Delta x \Delta y$$

Fourier's law

$$q_x = -k\frac{\partial T}{\partial x}$$

$$\rho \cdot c \cdot \frac{\partial T}{\partial t} = k\frac{\partial^2 T}{\partial x^2} \quad \text{or} \quad \frac{\partial T}{\partial t} = \alpha\frac{\partial^2 T}{\partial x^2}$$

Boundary Conditions:

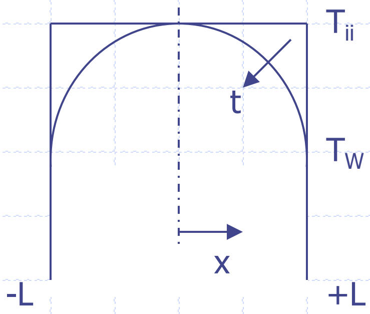
1st kind $\quad T(x = x') = \text{constant}$

2nd kind $\quad -k\frac{\partial T}{\partial x}(x = x') = \text{constant}$

3rd kind $\quad -k\frac{\partial T}{\partial x}(x = x') = \bar{h}(T - T_\infty)$

The boundary condition of 1st kind applies to injection molding since the tool is often maintained at a constant temperature

Heat transfer



Let L_{ch} = H/2 (half thickness) = L ; $t_{ch} = L^2/\alpha$;
$\Delta T_{ch} = T_i - T_W$ (initial temp. – wall temp.)

Non-dimensionalize: $\theta = \dfrac{T - T_W}{T_i - T_W}; \quad \xi = \dfrac{x}{L} + 1; \quad F_O = \dfrac{\alpha \cdot t}{L^2}$

Dimensionless equation:

$$\frac{\partial \theta}{\partial F_O} = \frac{\partial^2 \theta}{\partial \xi^2}$$

Initial condition $\quad F_O = 0 \qquad \theta = 1$

Boundary condition $\quad \xi = 0 \qquad \theta = 0$

$\quad \xi = 2 \qquad \theta = 0$

Separation of variables ;
matching B.C.; matching I.C.

$$\theta(\xi, F_O) = \sum f(F_O) g(\xi)$$

Temperature in a slab

Centerline, $\theta = 0.1$, $F_o = \alpha t/L^2 = 1$

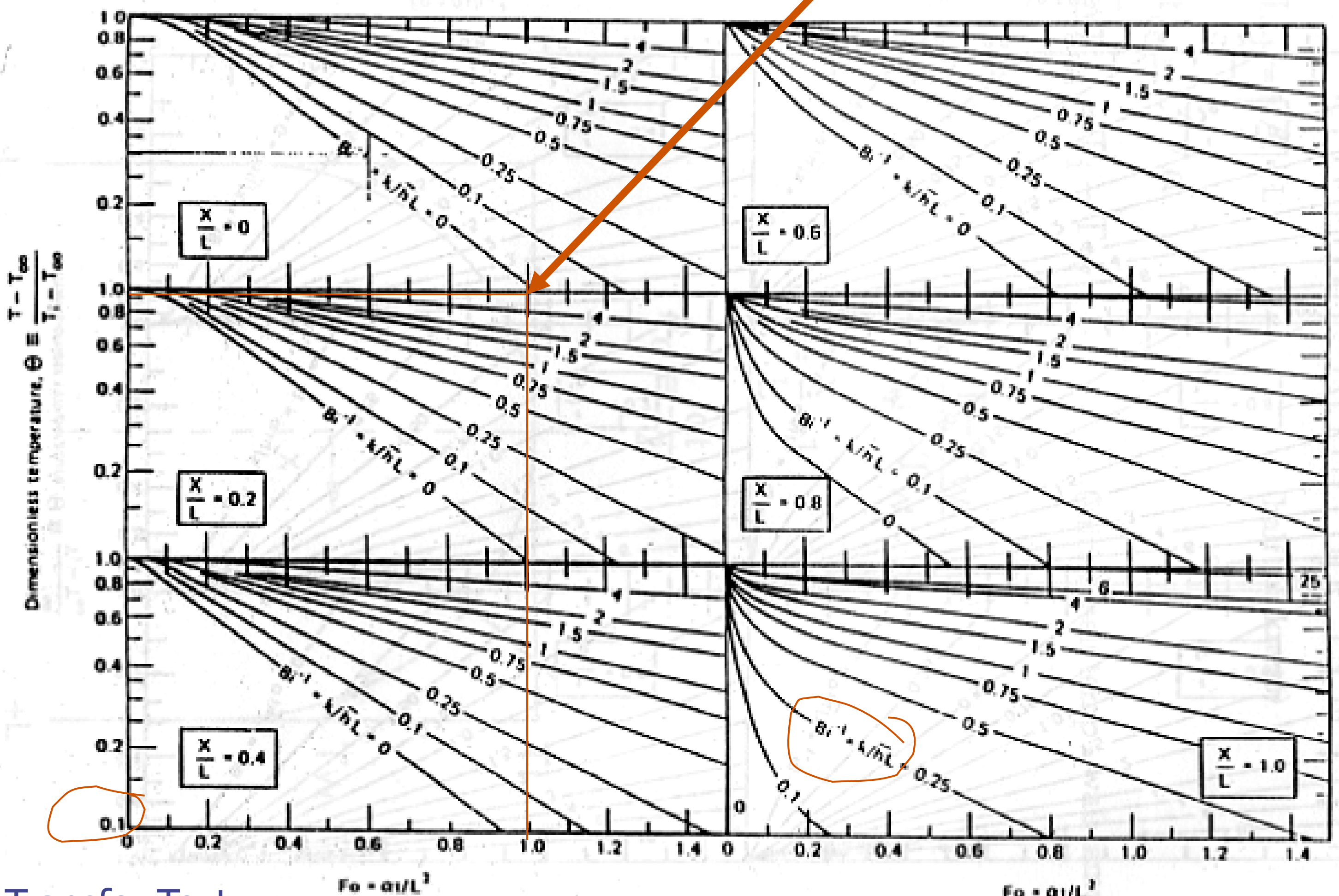


FIGURE 5.7 The transient temperature distribution in a slab at six positions. x/L = 0 is the center; x/L = 1 is one outside boundary.

See Heat Transfer Text
By Lienhard on line

$Bi^{-1} = k/hL$

Reynolds Number

Reynolds Number:

$$\mathrm{Re} = \frac{\rho \frac{V^2}{L} \quad \text{inertia}}{\mu \frac{V}{L^2} \quad \text{viscous}} = \frac{\rho V L}{\mu}$$

For typical injection molding

$$\rho = 1 g/cm^3 = 10^3 N/m^4/s^2; \quad L_Z = 10^{-3} m \quad \text{thickness}$$

$$V \approx \frac{\text{Part length}}{\text{Fill time}} = \frac{10^{-1}}{1s}; \qquad \mu = 10^3 N \cdot s/m^2$$

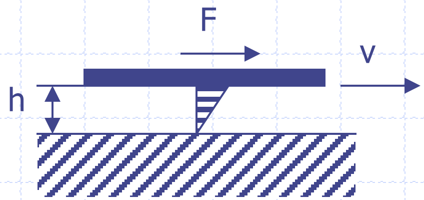
$$\mathrm{Re} = 10^{-4}$$

For Die casting

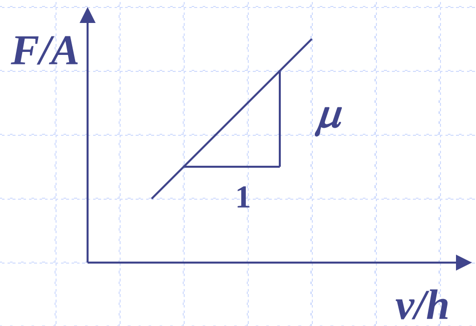
$$\mathrm{Re} \approx \frac{3 \cdot 10^3 \times 10^{-1} \times 10^{-3}}{10^{-3}} = 300$$

* Source: http://www.idsa-mp.org/proc/plastic/injection/injection_process.htm

Viscous Shearing of Fluids



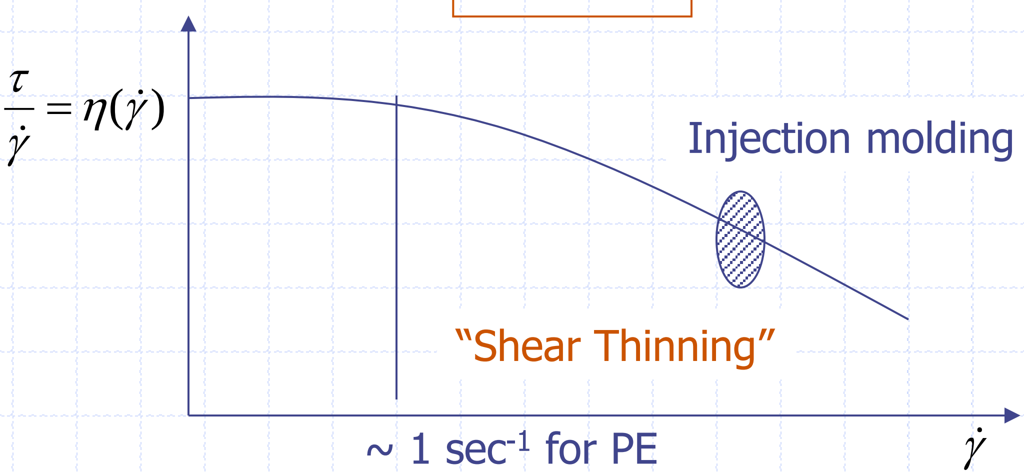
$$\frac{F}{A} \propto \frac{v}{h}$$



Newtonian Viscosity

$$\tau = \mu \frac{v}{h}$$

Generalization: $\tau = \mu \dot{\gamma}$ $\dot{\gamma}$: shear rate



Typical shear rate for Polymer processes $(sec)^{-1}$

Extrusion	$10^2 \sim 10^3$
Calendering	$10 \sim 10^2$
Injection molding	$10^3 \sim 10^4$
Comp. Molding	$1 \sim 10$

Viscous Heating

Rate of Heating
= Rate of Viscous Work

$$\frac{P}{Vol} = \frac{F \cdot v}{Vol} = \frac{F}{A} \cdot \frac{v}{h} : \mu\left(\frac{v}{h}\right)^2$$

Rate of Temperature rise

$$\rho \cdot c_p \frac{dT}{dt} = \mu\left(\frac{v}{h}\right)^2 \quad \text{or} \quad \frac{dT}{dt} = \frac{\mu}{\rho \cdot c_p}\left(\frac{v}{h}\right)^2$$

Rate of Conduction out

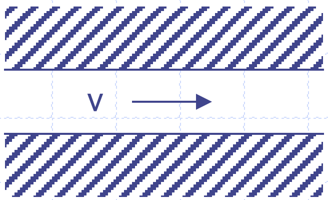
$$\frac{dT}{dt} = \frac{k}{\rho \cdot c_p} \frac{d^2T}{dx^2} \sim \frac{k}{\rho \cdot c_p} \frac{\Delta T}{h^2}$$

$$\frac{\text{Viscous heating}}{\text{Conduction}} = \frac{\mu v^2}{k \Delta T}$$

Brinkman number

For injection molding, order of magnitude ~ 0.1 to 10

Non-Isothermal Flow



Flow rate: $1/t \sim V/L_x$

Heat transfer rate: $1/t \sim a/(L_z/2)^2$

Péclet No.

$$\frac{\text{Flow rate}}{\text{Heat xfer rate}} \sim \frac{V \cdot L_z^2}{4\alpha \cdot L_x} = \frac{1}{4}\frac{VL_z}{\alpha} \cdot \frac{L_z}{L_x}$$

Small value
=> Short shot

For injection molding

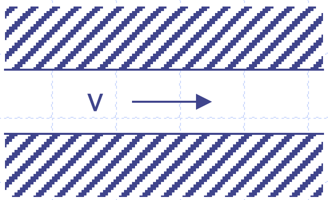
$$\frac{\text{Flow rate}}{\text{Heat xfer rate}} \sim \frac{1}{4}\frac{10cm/s \times 0.1cm}{10^{-3}cm^2/s} \cdot \frac{0.1cm}{10cm} = 2.5$$

For Die casting of aluminum

$$\frac{\text{Flow rate}}{\text{Heat xfer rate}} \sim \frac{1}{4}\frac{10cm/s \times 0.1cm}{0.3cm^2/s} \cdot \frac{0.1cm}{10cm} \cong 10^{-2}$$

* Very small, therefore it requires thick runners

Non-Isothermal Flow



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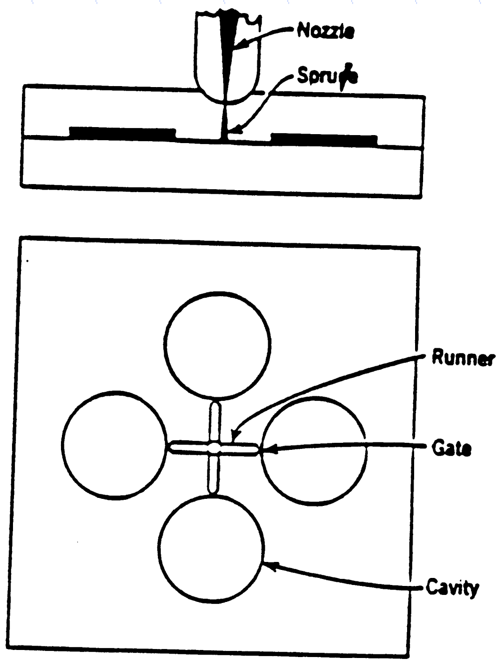
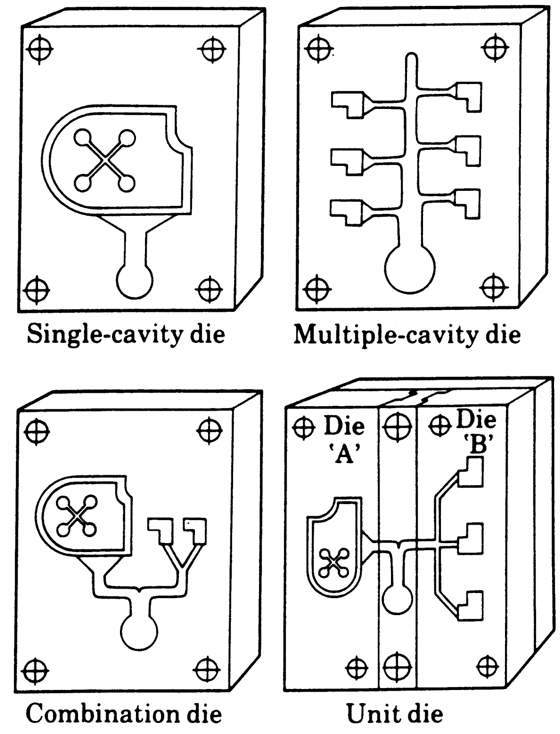
Very small value for aluminum requires thicker runners

Injection mold   die cast mold





Fountain Flow

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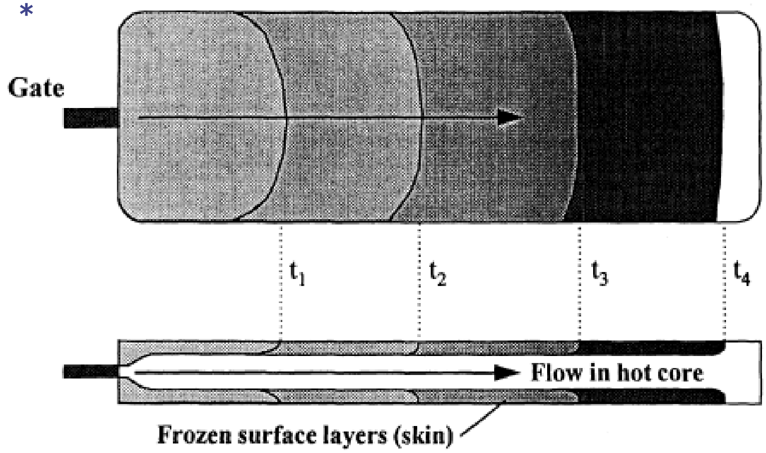

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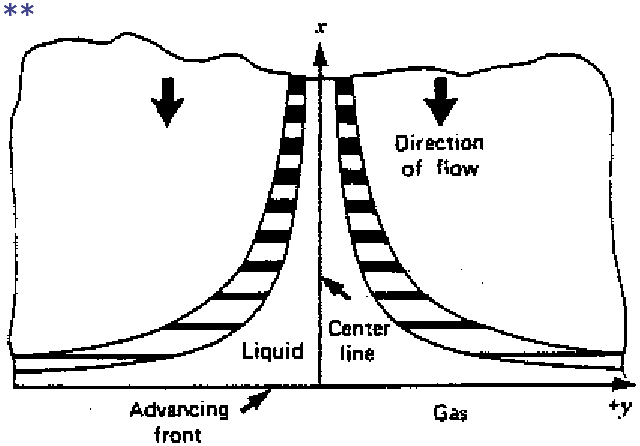
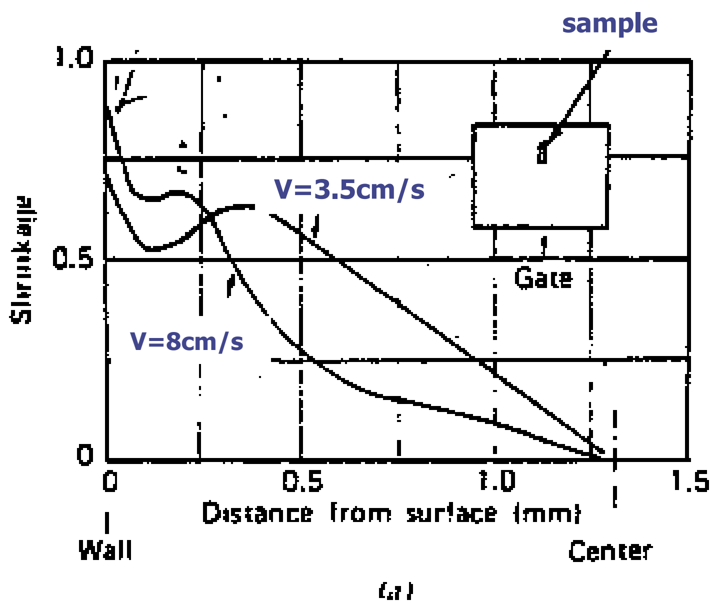
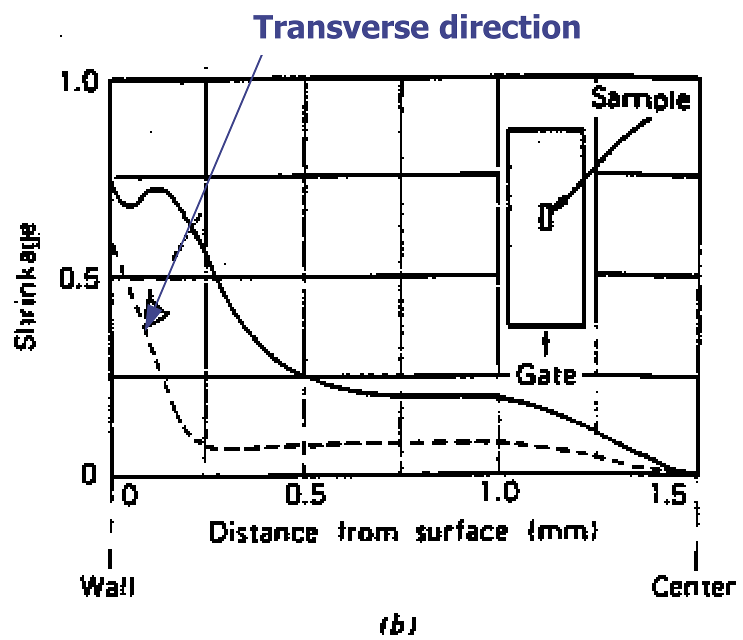


* Source: http://islnotes.cps.msu.edu/trp/inj/flw_froz.html ; ** Z. Tadmore and C. Gogos, "Principles of Polymer Processing"

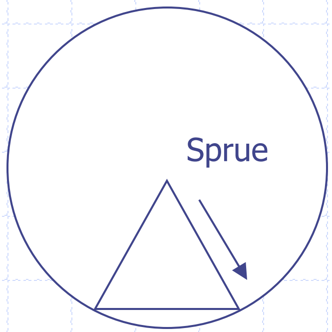
Shrinkage distributions

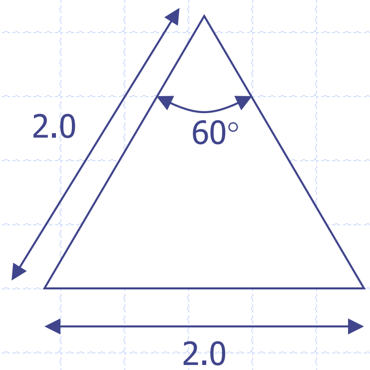




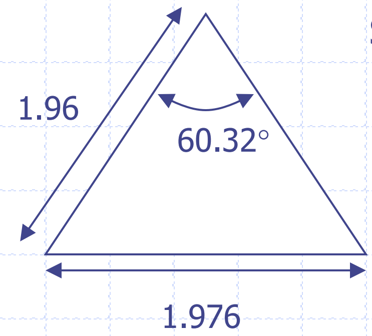
* Source: G. Menges and W. Wubken, "Influence of processing conditions on Molecular Orientation in Injection Molds"

Gate Location and Warping



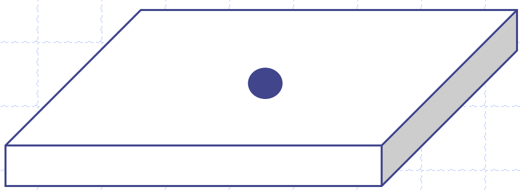


Before shrinkage



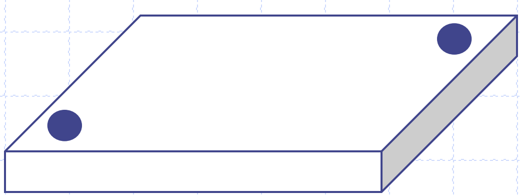
After shrinkage

Shrinkage
Direction of flow – 0.020 in/in
Perpendicular to flow – 0.012



Center gate: radial flow – severe distortion

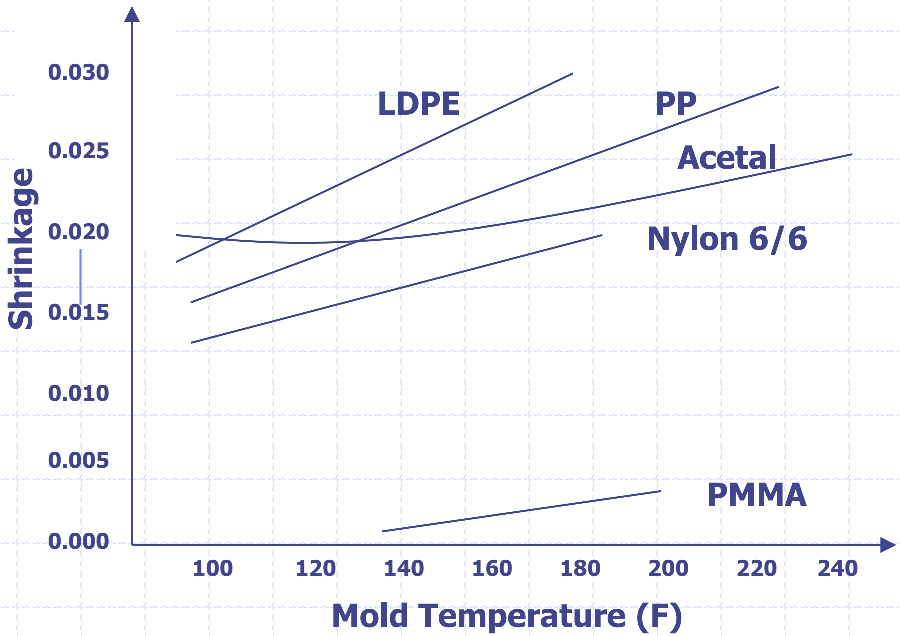
Edge gate: warp free, air entrapment

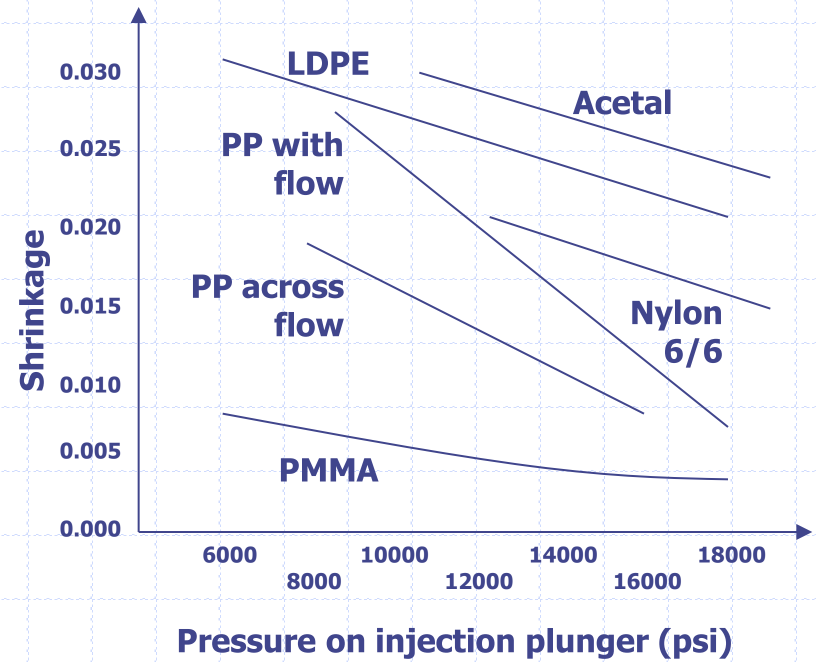


Diagonal gate: radial flow – twisting

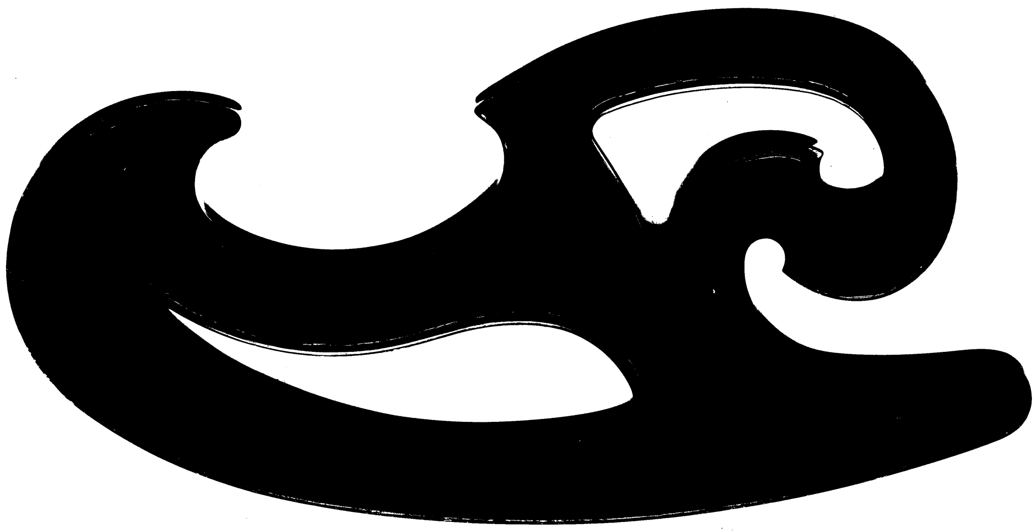
End gates: linear flow – minimum warping

Effects of mold temperature and pressure on shrinkage

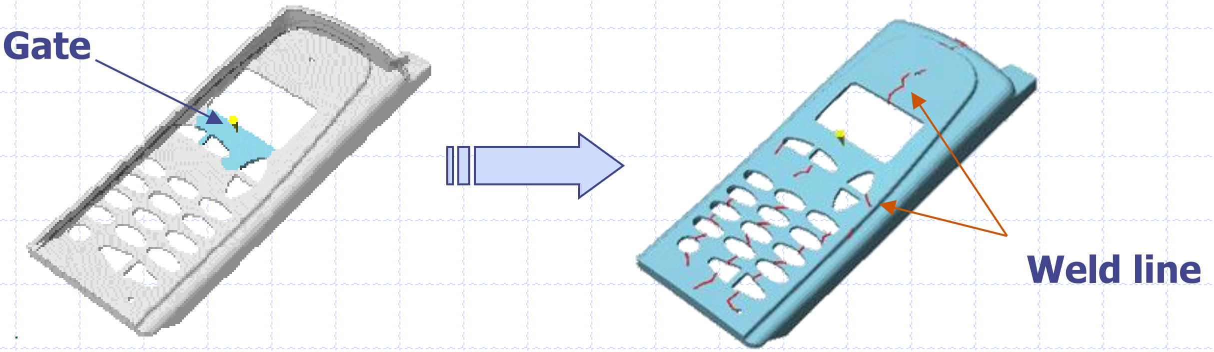




Where would you gate this part?

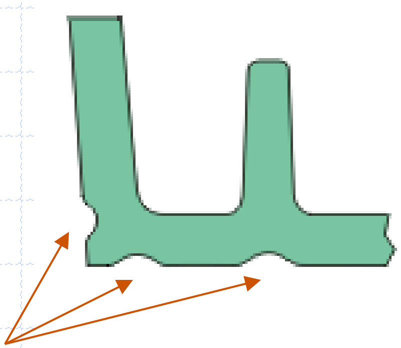


Weld line, Sink mark

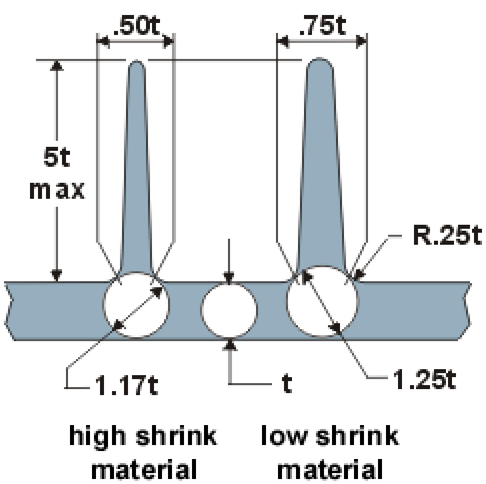


Mold Filling

Solidified part



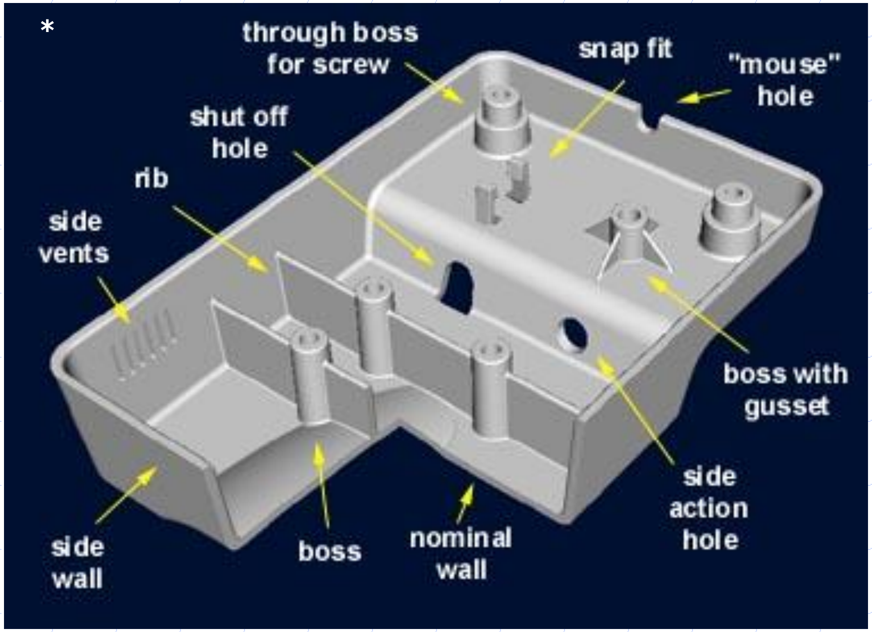
Sink mark

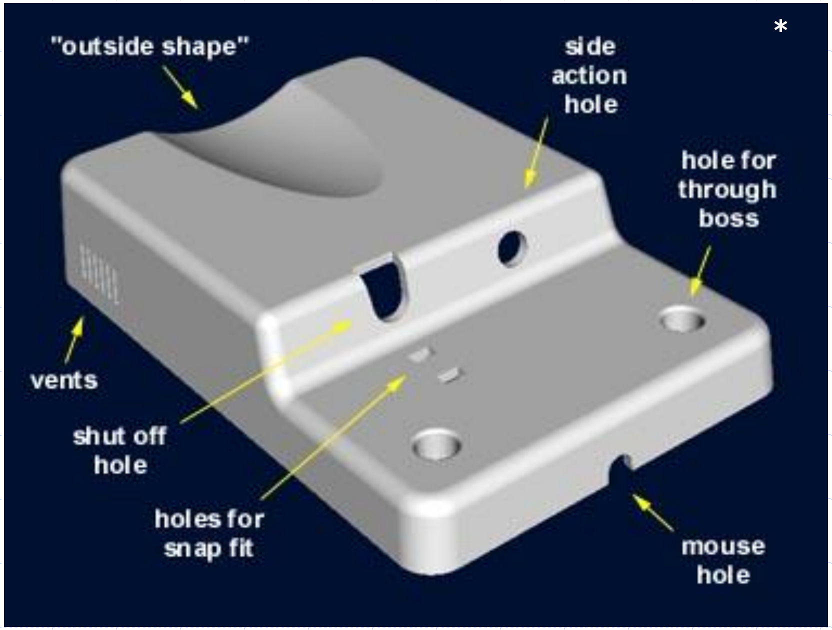


Basic rules in designing ribs to minimize sink marks

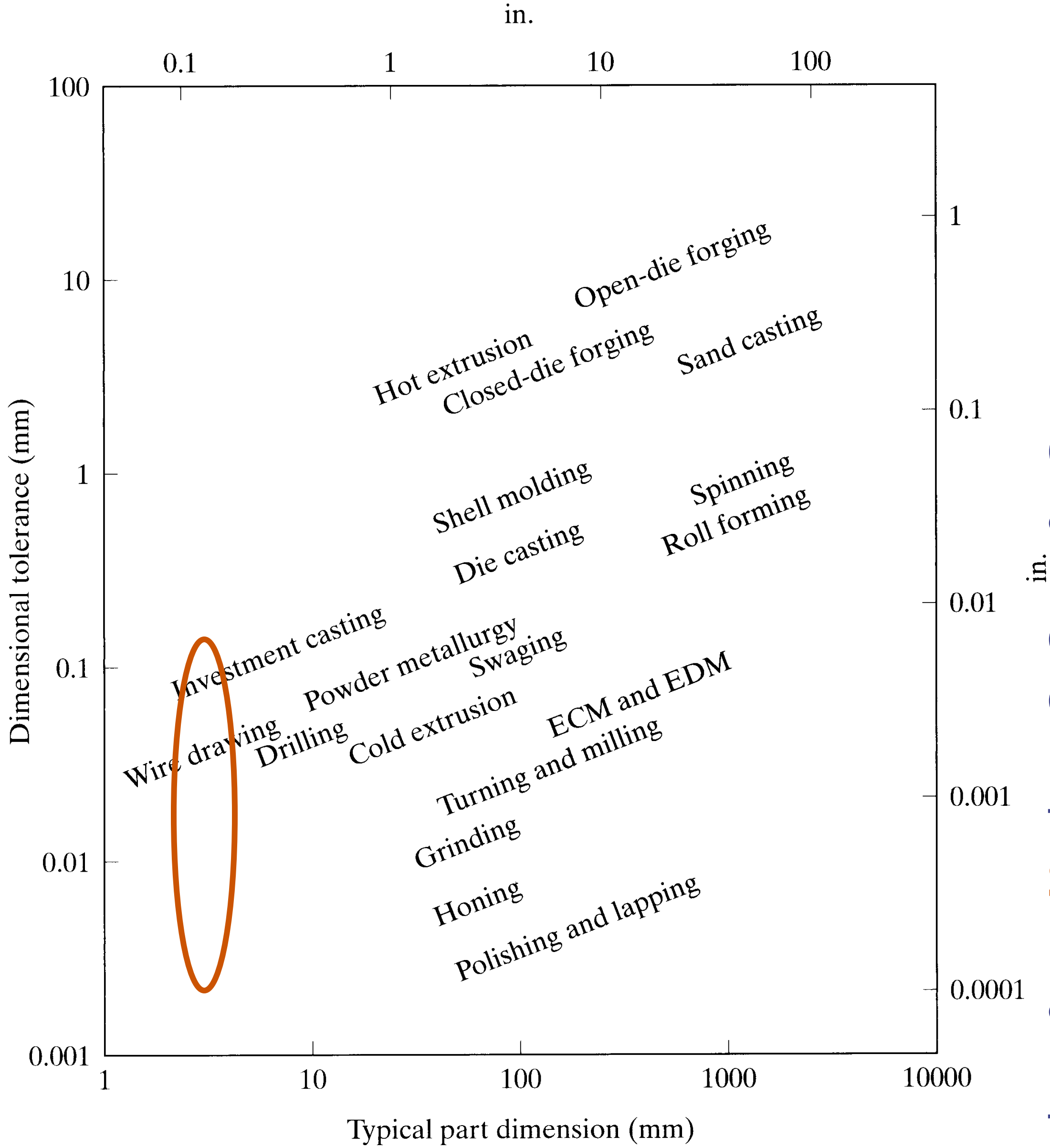
* Source: http://www.idsa-mp.org/proc/plastic/injection/injection_design_7.htm

Injection Molding





* Source: http://www.idsa-mp.org/proc/plastic/injection/injection_design_2.htm

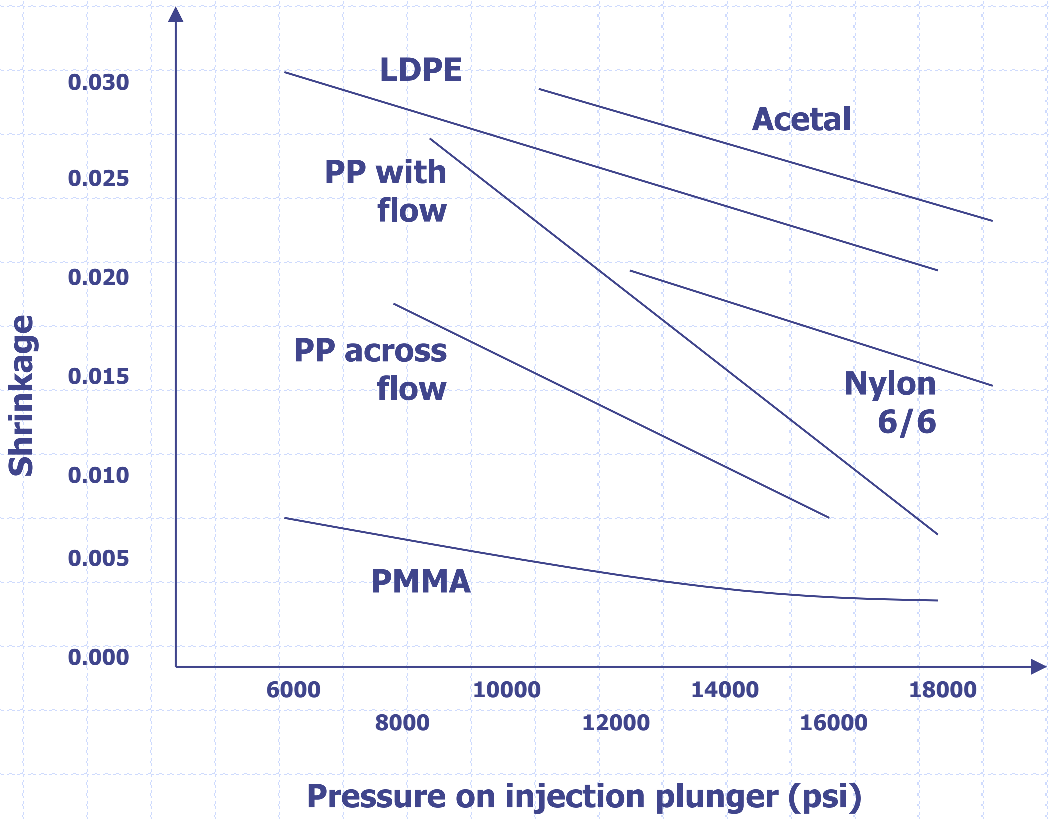


Where is injection molding?

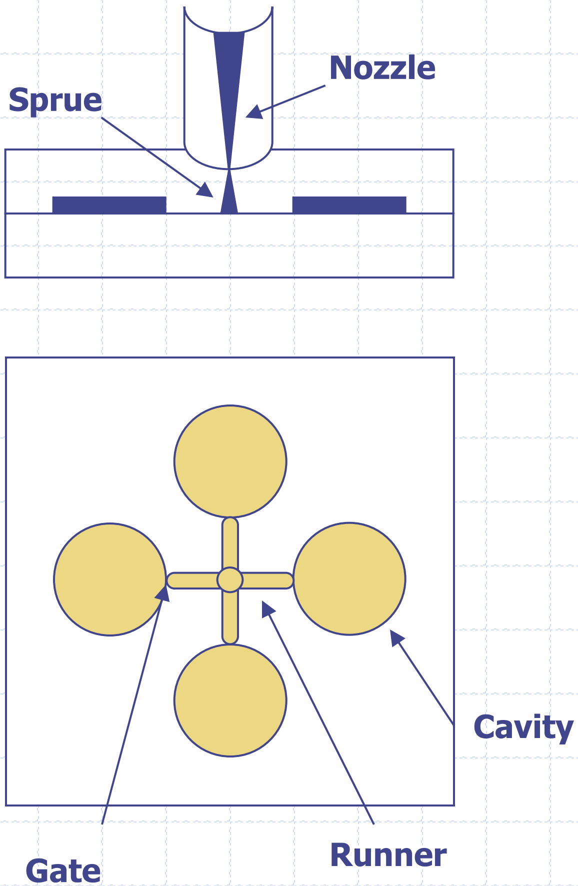
Controlled by shrinkage and warping. Hence, polymer, fillers, mold geometry and processing conditions can all influence the final tolerance.

Shrinkage is of order 10-100/1000 for unfilled and
1-10/1000 for filled across the thickness

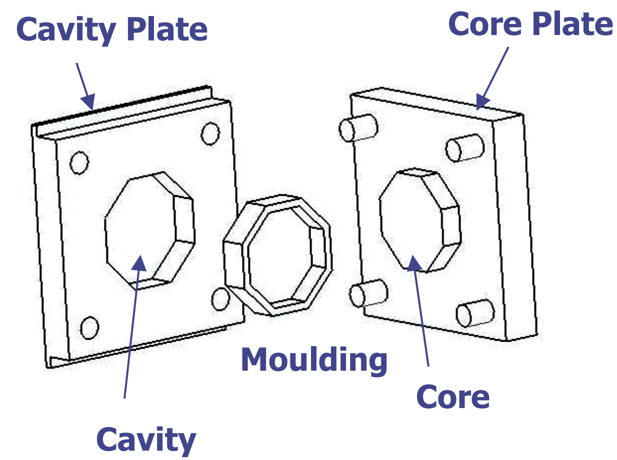
Effects of mold pressure on shrinkage



Tooling Basics

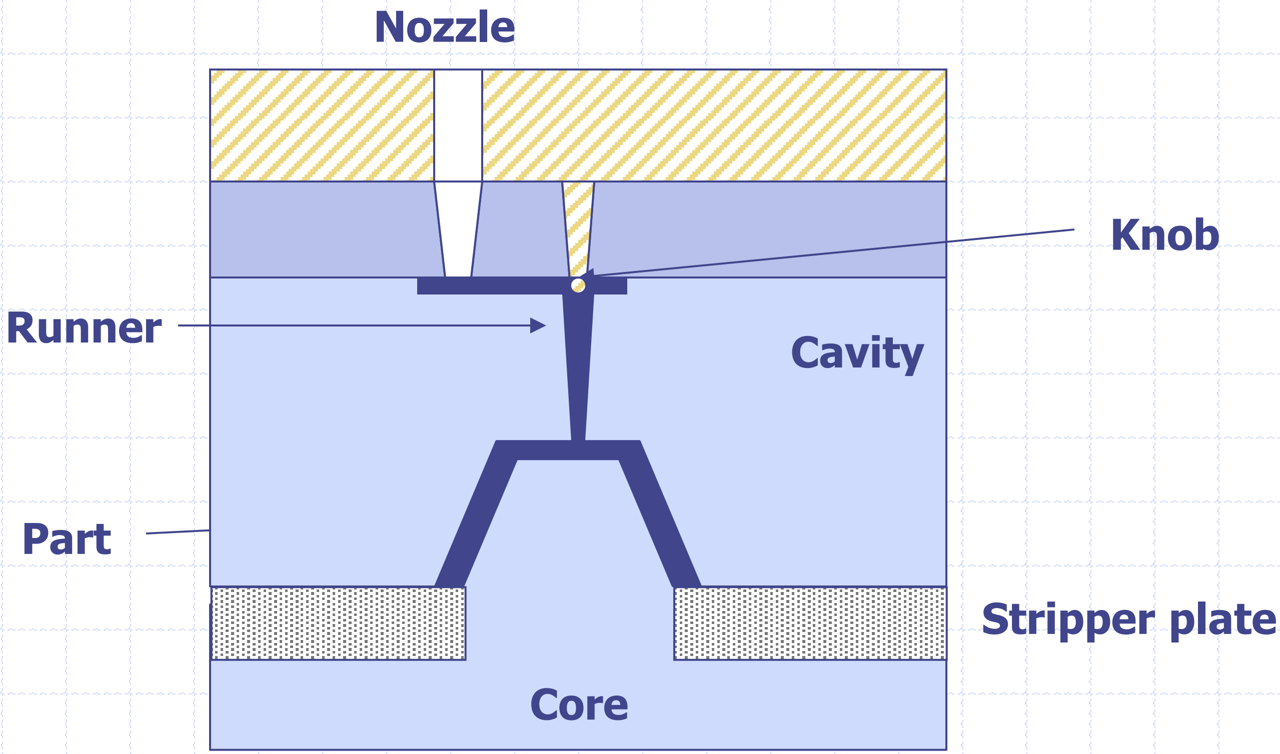


Melt Delivery

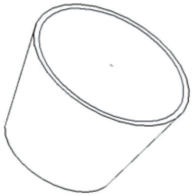


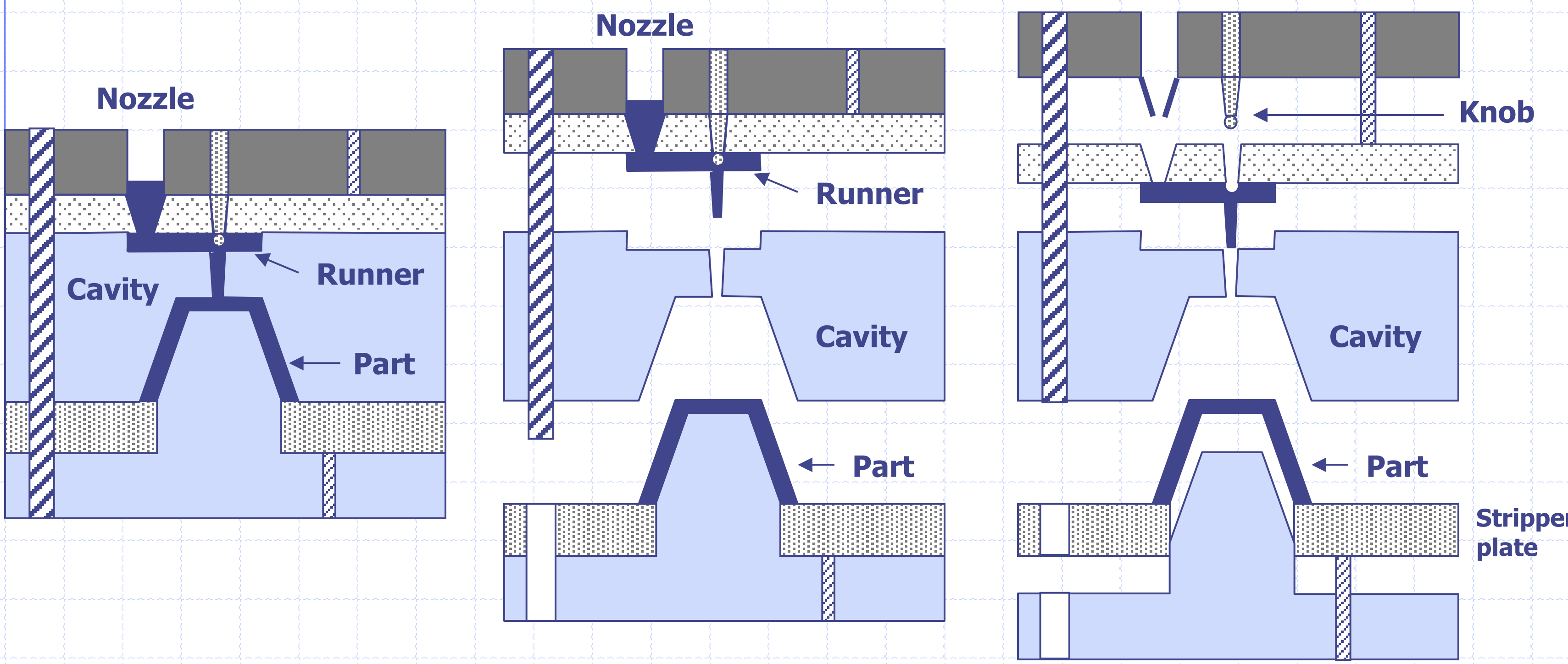
Basic mould consisting of cavity and core plate

Tooling for a plastic cup

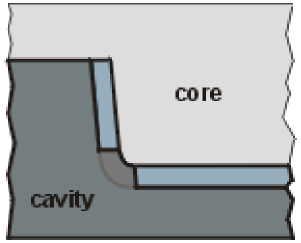


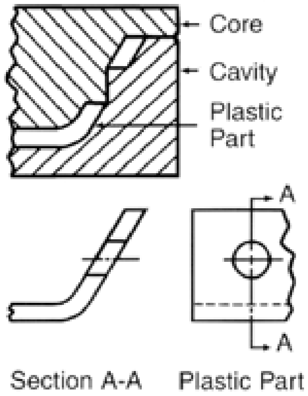
Tooling for a plastic cup

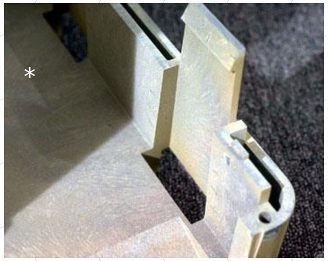


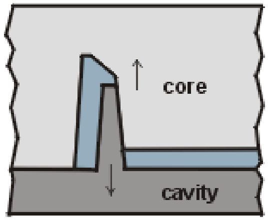


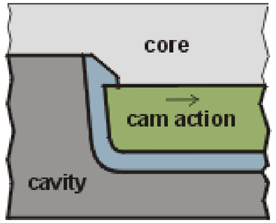
Tooling

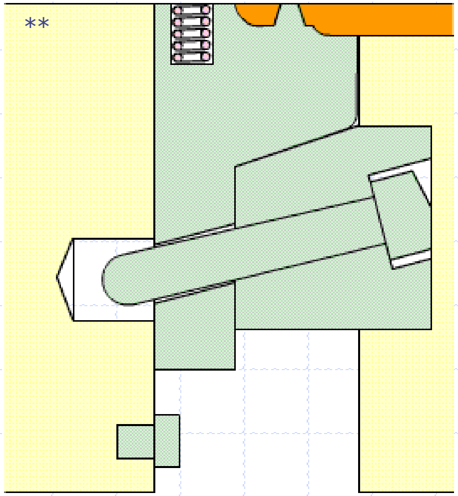












* Source: http://www.idsa-mp.org/proc/plastic/injection/; ** http://www.hzs.co.jp/english/products/e_trainer/mold/basic/basic.htm (E-trainer by HZS Co.,Ltd.)

Tooling Alternatives

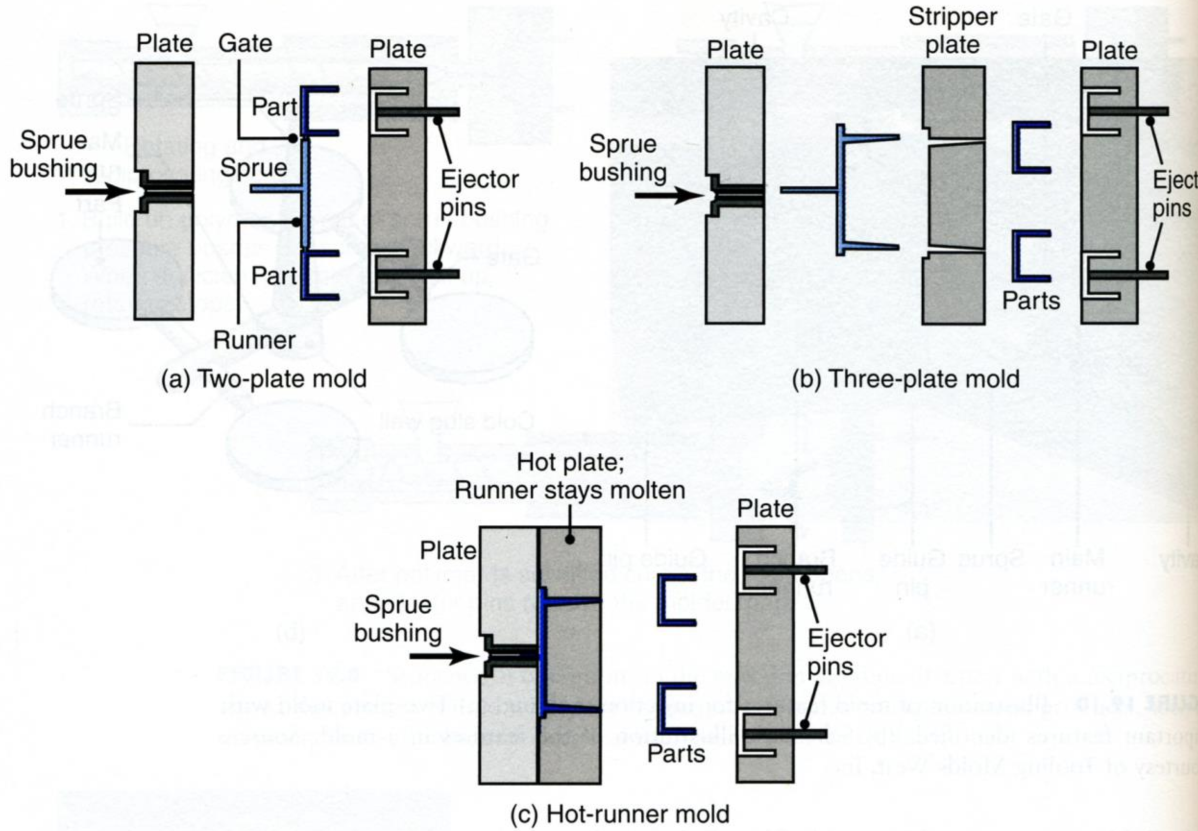


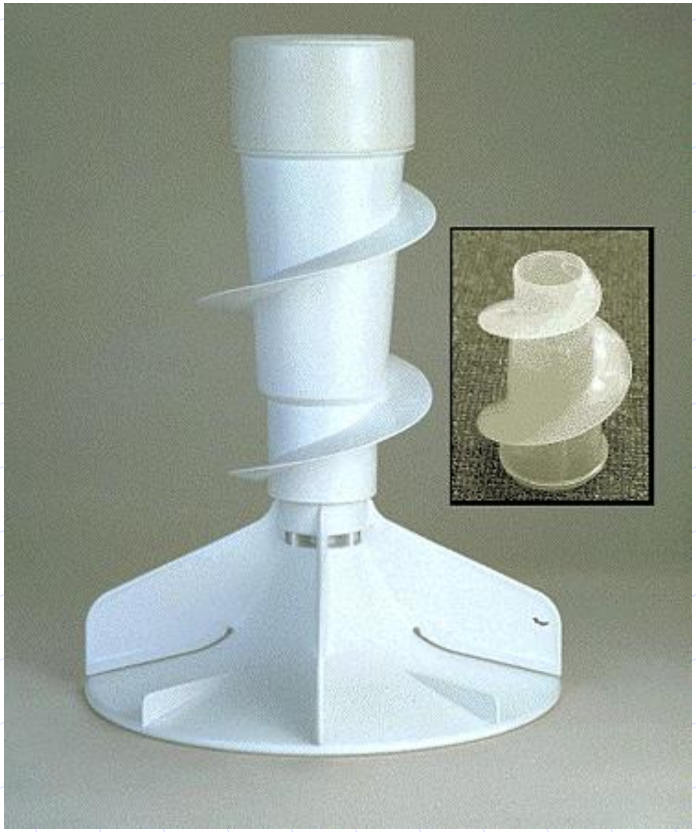
FIGURE 19.11 Types of molds used in injection molding.

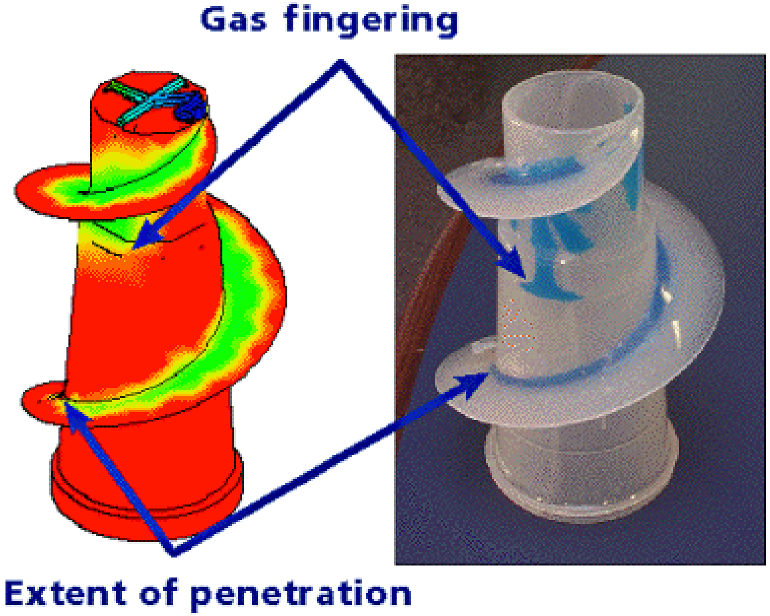
Kalpakjian & Schmid

Part design rules

- Simple shapes to reduce tooling cost
  - No undercuts, etc.
- Draft angle to remove part
  - In some cases, small angles (1/4°) will do
  - Problem for gears
- Even wall thickness
- Minimum wall thickness ~ 0.025 in
- Avoid sharp corners
- Hide weld lines
  - Holes may be molded 2/3 of the way through the wall only, with final drilling to eliminate weld lines

New developments- Gas assisted injection molding





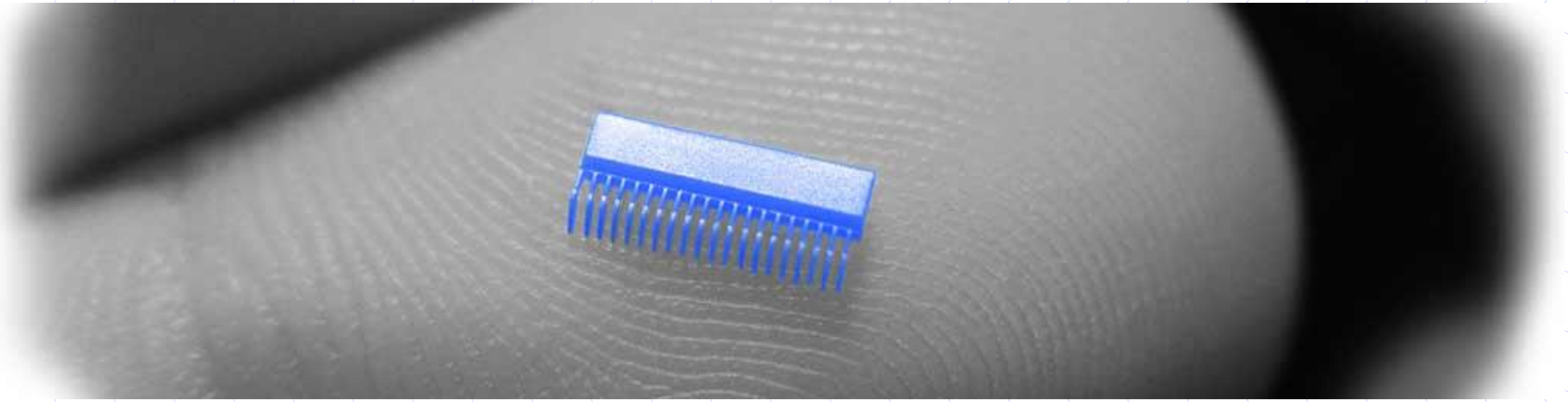
New developments ; injection molding with cores

Injection Molded Housing

Cores used in Injection Molding

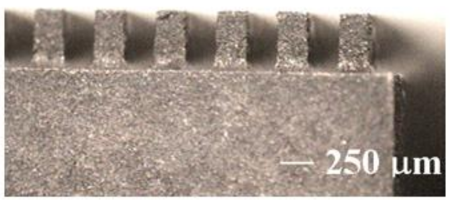
Cores and
Part Molded in Clear Plastic

Micro injection molding

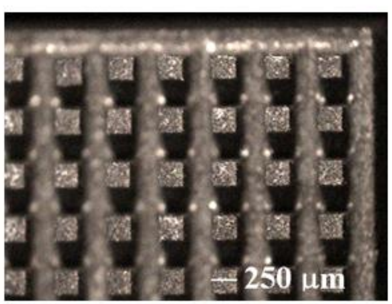


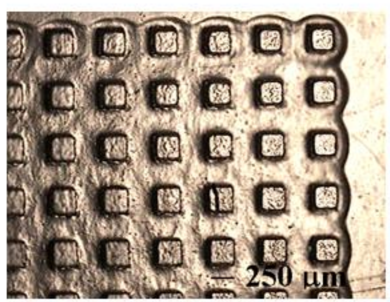
Micro embossing

Replacing serial processes with parallel processes at small scales

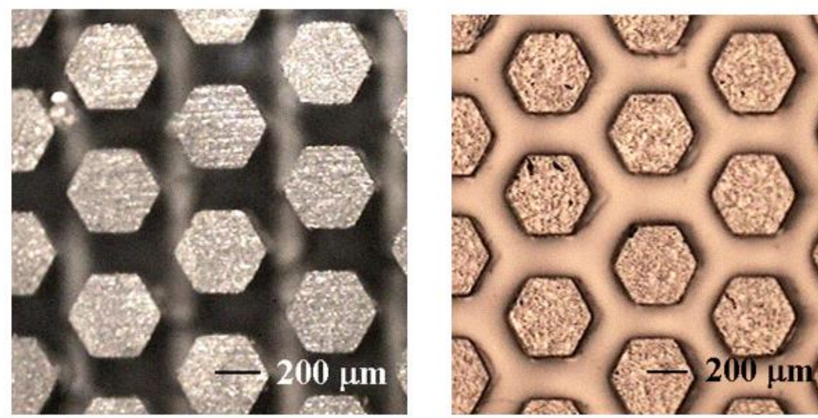


h) Side view of wire EDM stainless steel micro well embossing insert





i) Micro well embossing insert (top view) j) HDPE embossed micro wells

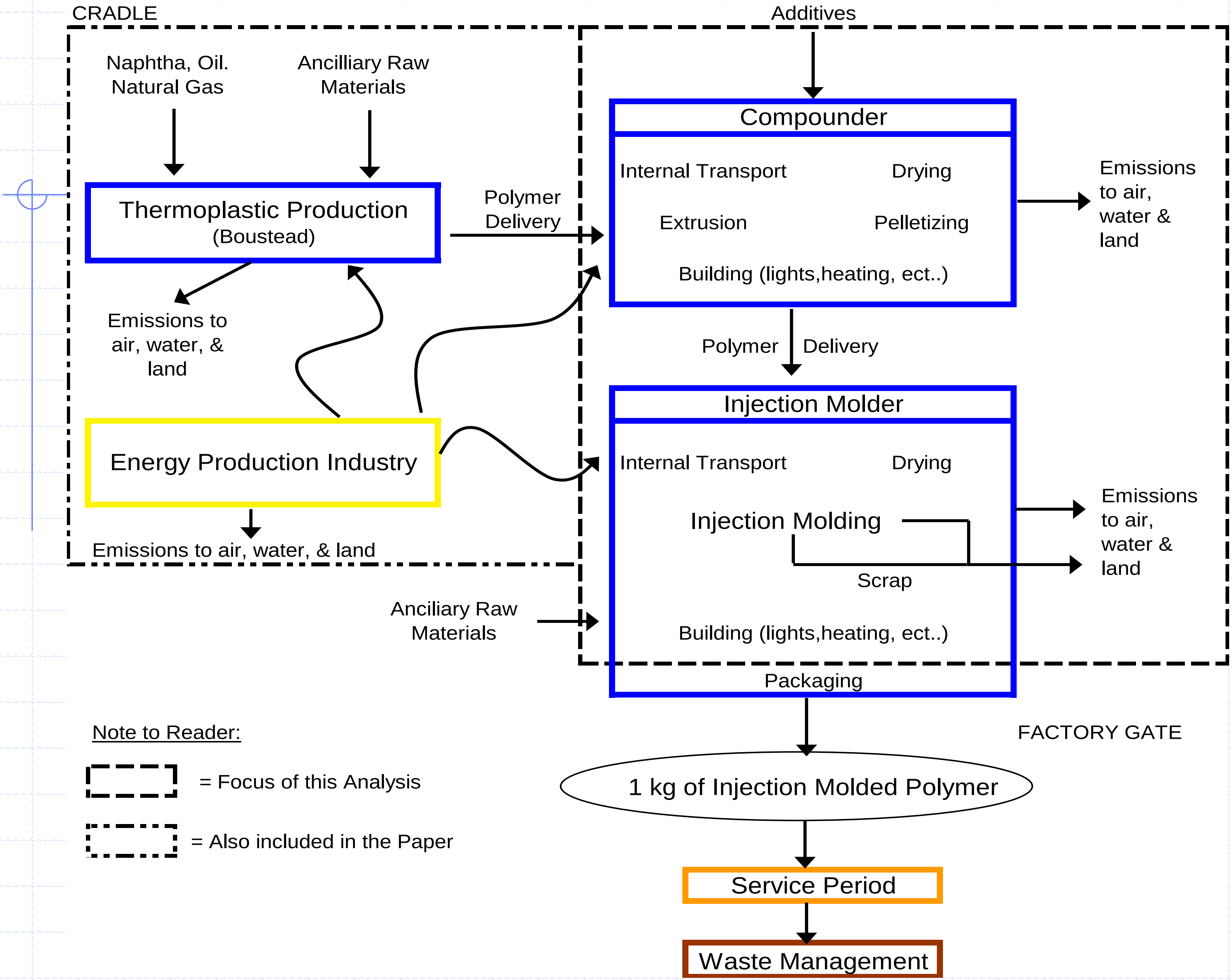


k) Hexagonal micro well embossing insert (Mezzo Systems Inc.) and HDPE embossed hexagonal micro wells

B. Kim UMass

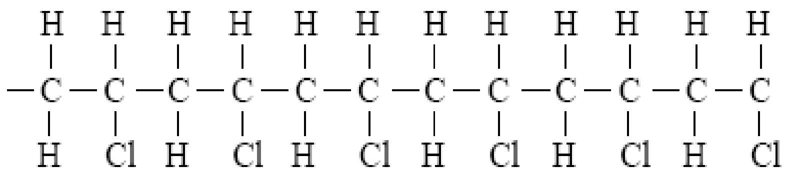
Environmental issues

- System boundaries
- Polymer production
- Compounding
- Machine types
- Out gassing & energy during processing


CRADLE
Additives
Naphtha, Oil. Natural Gas
Ancilliary Raw Materials
Thermoplastic Production
(Boustead)
Polymer Delivery
Compounder
Internal Transport
Drying
Extrusion
Pelletizing
Building (lights,heating, ect..)
Emissions to air, water & land
Emissions to air, water, & land
Polymer Delivery
Injection Molder
Energy Production Industry
Internal Transport
Drying
Injection Molding
Emissions to air, water & land
Emissions to air, water, & land
Scrap
Anciliary Raw Materials
Building (lights,heating, ect..)
Packaging
Note to Reader:
= Focus of this Analysis
= Also included in the Paper
FACTORY GATE
1 kg of Injection Molded Polymer
Service Period
Waste Management

Polymer Production
Largest Player in the Injection Molding LCI

What is a polymer:



How much energy does it take to make 1 kg of polymer = a lot !!!

Sources	HDPE	LLDPE	LDPE	PP	PVC	PS	PC	PET
Boustead	76.56	77.79	73.55	72.49	58.41	86.46	115.45	77.14
Ashby	111.50	-------	92.00	111.50	79.50	118.00	-------	-------
Patel	-------	-------	64.60	-------	53.20	70.80	80.30	59.40
Kindler/Nickles [Patel 1999]	-------	-------	71.00	-------	53.00	81.00	107.00	96.00
Worrell et al. [Patel 1999]	-------	-------	67.80	-------	52.40	82.70	78.20	
E^3 Handbook [OIT 1997]	131.65	121.18	136.07	126.07	33.24	-------	-------	-------
Energieweb	80.00	-------	68.00	64.00	57.00	84.00	-------	81.00

Values are in MJ per kg of polymer produced.

Thiriez '06

Compounding - extrusion

- An extruder is used to mix additives with a polymer base, to bestow the polymer with the required characteristics.
- Similar to an injection molding machine, but without a mold and continuous production.
- Thus it has a similar energy consumption profile.

Environmentally Unfriendly Additives:

•Fluorinated blowing agents (GHG's)

•Phalates (some toxic to human liver, kidney and testicles)

•Organotin stabilizers (toxic and damage marine wildlife)

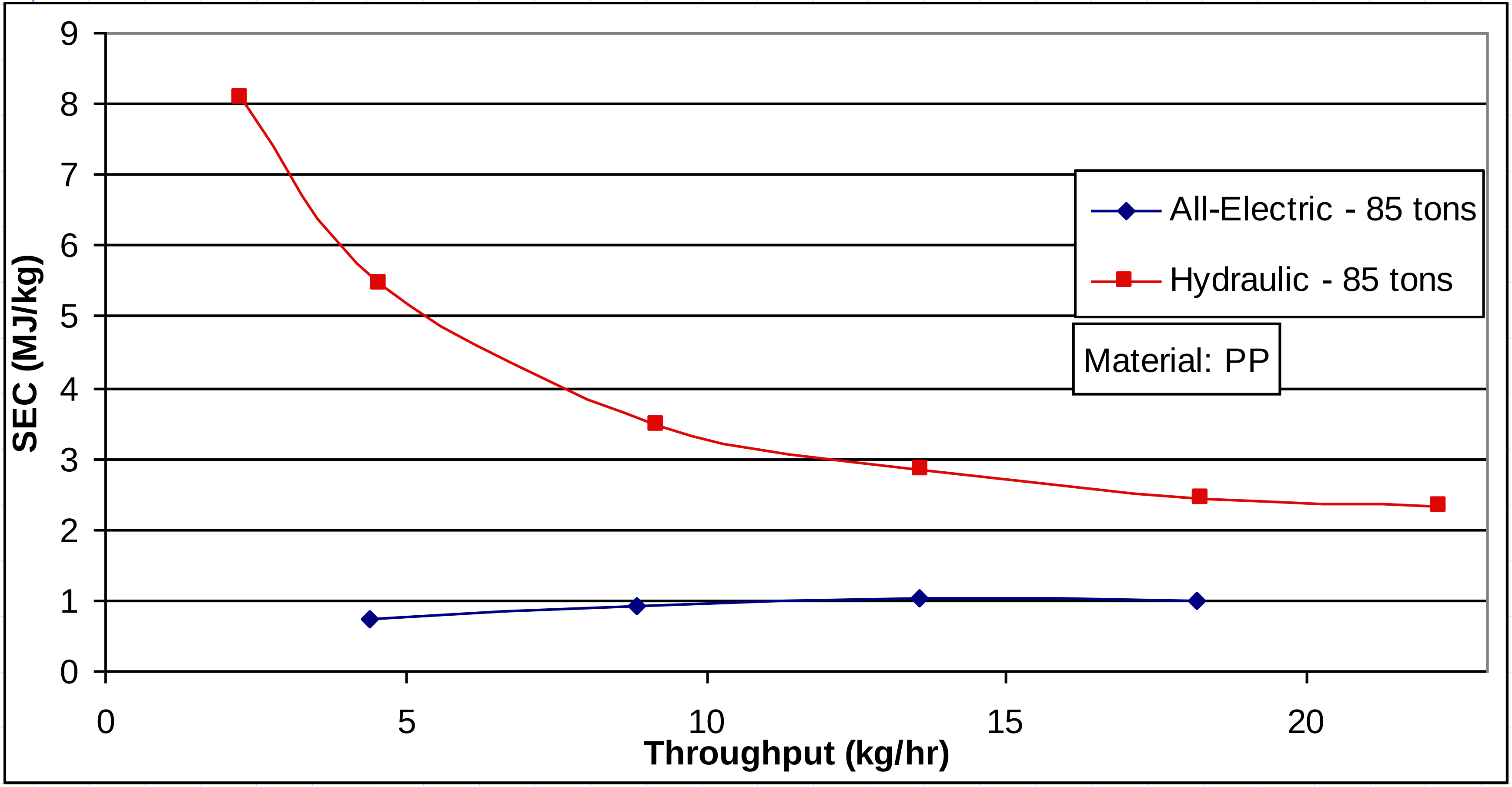
Injection Molding Process

Source: http://cache.husky.ca/pdf/brochures/br-hylectric03a.pdf

Machine types: Hydraulic, electric, hydro-electric

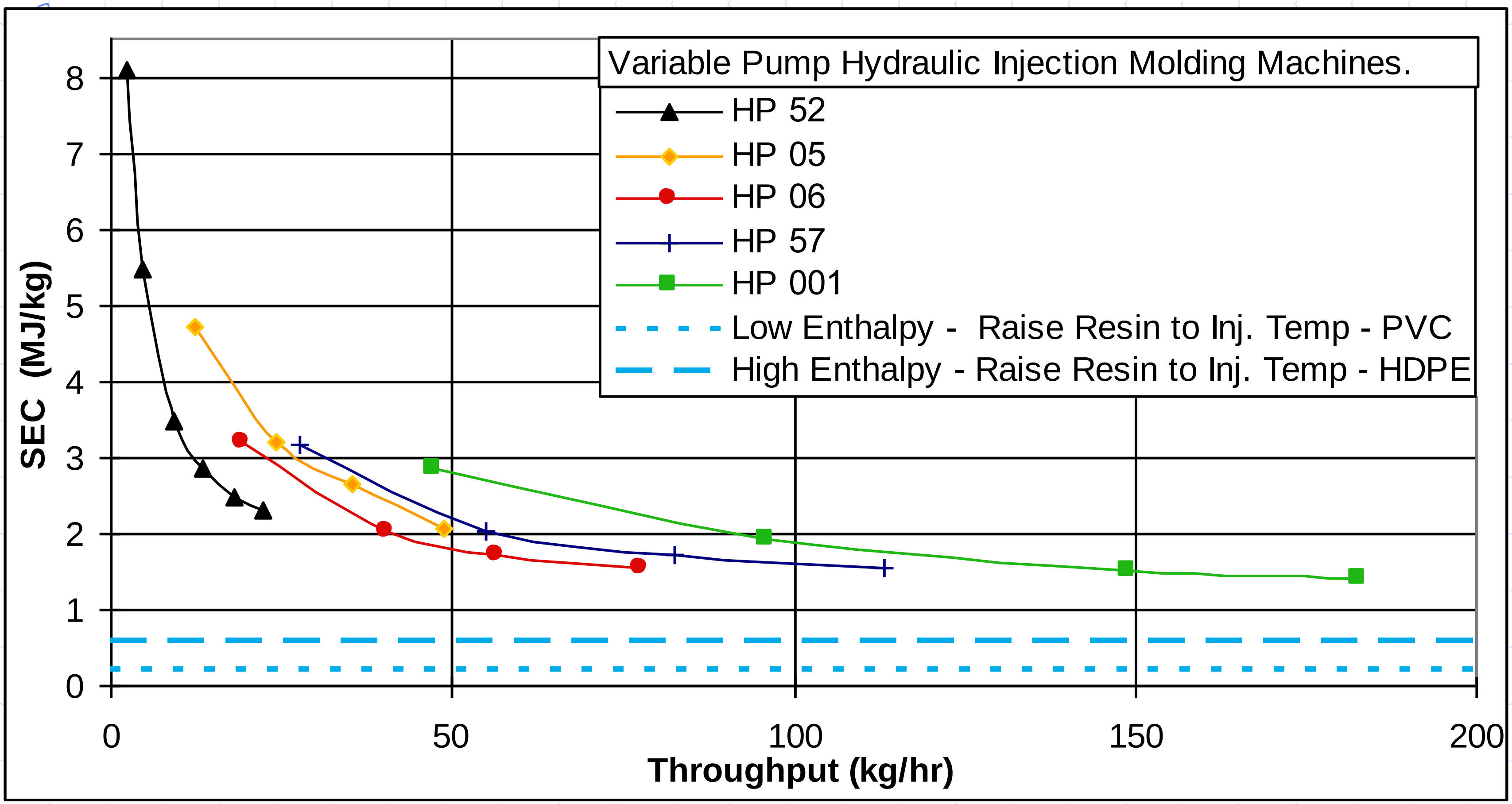
All-electrics have very low fixed energy costs (small idling power). SEC is constant as throughput increases.

$$SEC \approx p_v$$



Source: [Thiriez]

For Hydraulics and Hybrids as throughput increases, SEC → k.

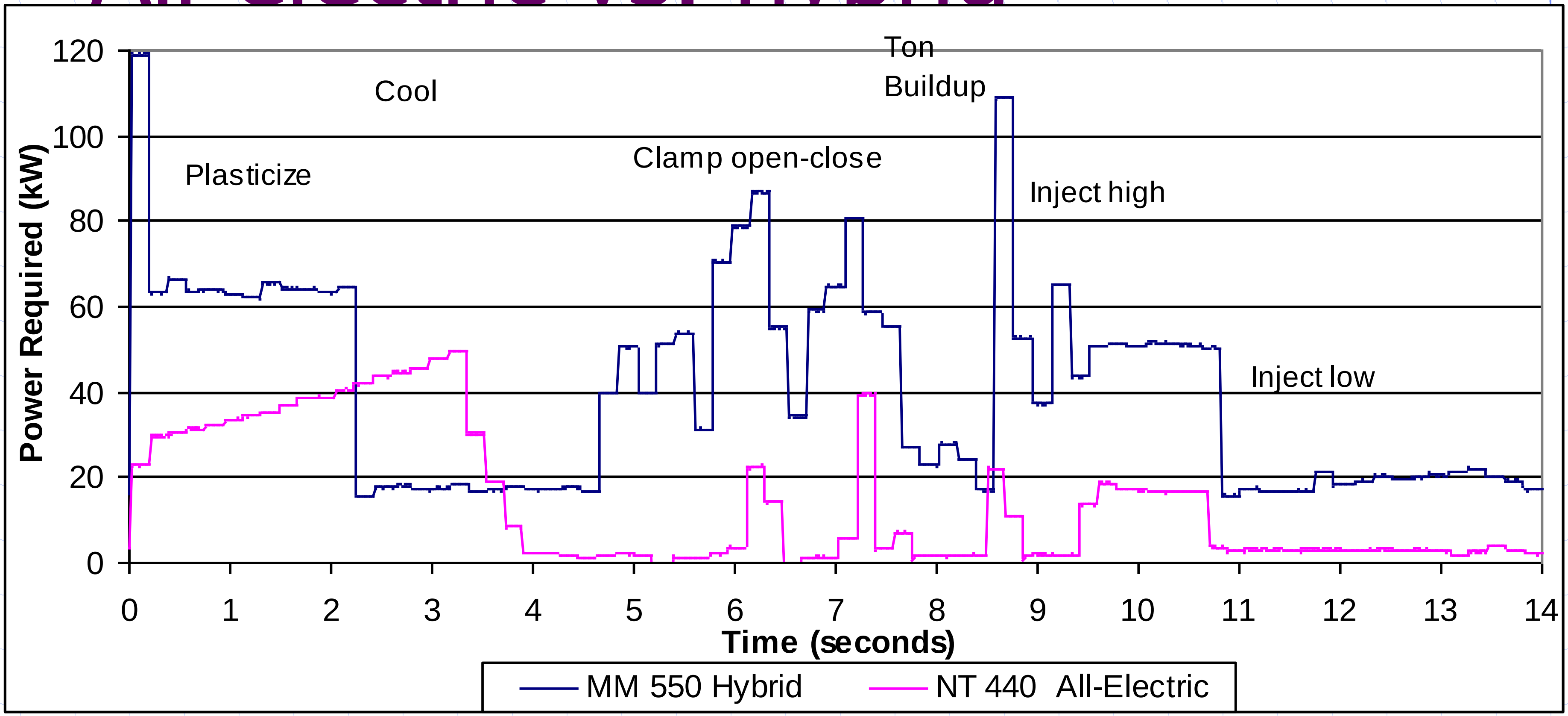


Does not account for the electric grid.

Source: [Thiriez]

Enthalpy value to melt plastics is just 0.1 to 0.7 MJ/kg !!!

All-electric vs. hybrid

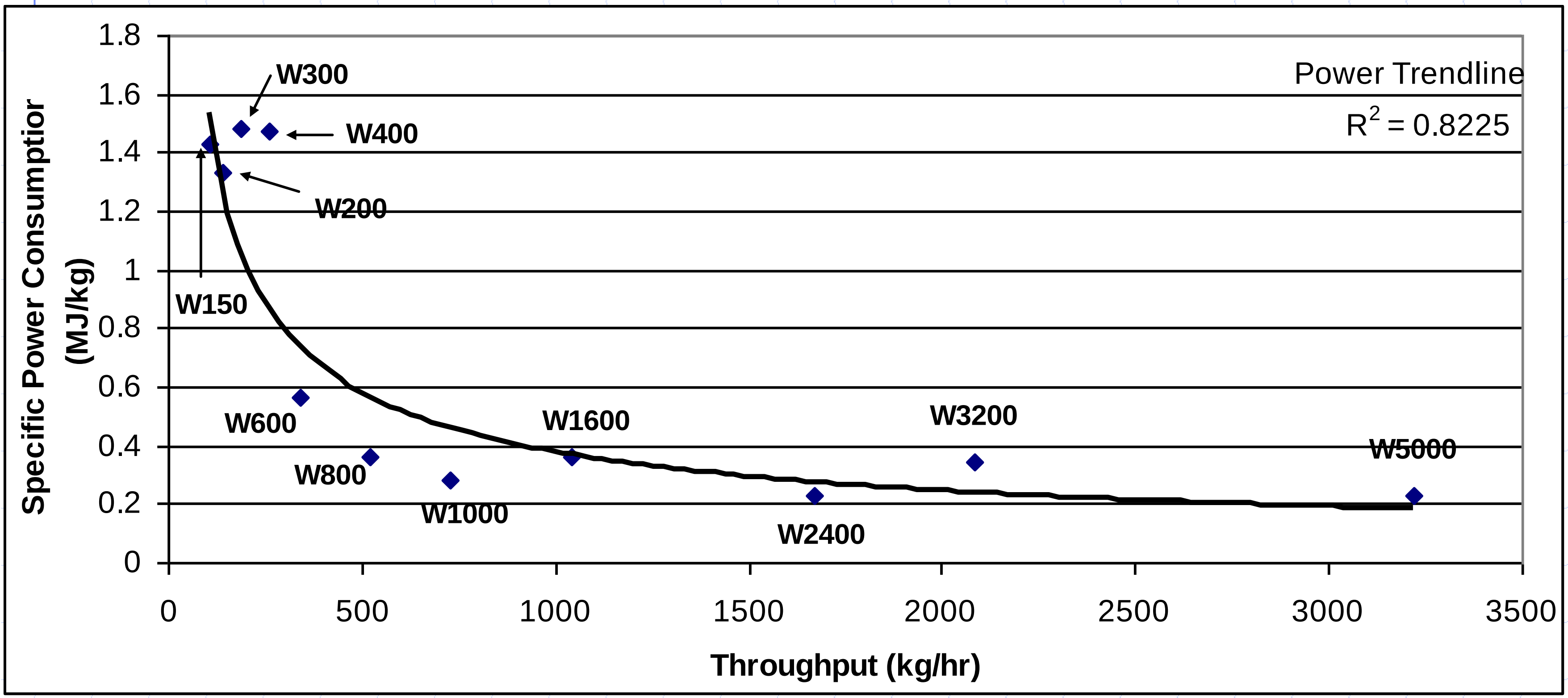


Source: [Thiriez]

The hydraulic plot would be even higher than the hybrid curve

Driers

- Used to dry internal moisture in hygroscopic polymers and external moisture in non-hygroscopic ones.
- It is done before extruding and injection molding.



Source: [Thiriez]

Same as

$$\frac{P}{\dot{m}} = \frac{E}{m} = SEC = \frac{P_0}{\dot{m}} + k$$

LCI Summarized Results

ENERGY CONSUMPTION BY STAGE in MJ/kg of shot

Thermoplastic Production

							Generic by Amount		Extras	
	HDPE	LLDPE	LDPE	PP	PVC	PS	Consumed	Inj. Molded	PC	PET
avg	89.8	79.7	73.1	83.0	59.2	87.2	81.2	74.6	95.7	78.8
low	77.9	79.7	64.6	64.0	52.4	70.8	69.7	62.8	78.2	59.4
high	111.5	79.7	92.0	111.5	79.5	118.0	102.7	97.6	117.4	96.0

Polymer Delivery	avg	0.19
	low	0.12
	high	0.24

Compounder

	Internal Transport	Drying	Extrusion	Pelletizing	Building (lights, heating, ect..)
avg	0.09	0.70	3.57	0.16	0.99
low	-----	0.30	1.82	0.06	-----
high	-----	1.62	5.00	0.31	-----

Subtotal

avg	5.51
low	3.25
high	8.01

Polymer Delivery	avg	0.19
	low	0.12
	high	0.24

Injection Molder

	Internal Transport	Drying	Injection Molding (look below)	Scrap (Granulating)	Building (lights, heating, ect..)
avg	0.04	0.70		0.05	0.99
low	-----	0.30		0.03	-----
high	-----	1.62		0.12	-----

		Injection Molding - Choose One		
		Hydraulic	Hybrid	All-Electric
	avg	11.29	5.56	4.89
	low	3.99	3.11	1.80
	high	69.79	8.45	15.29
Subtotal	avg	13.08	7.35	6.68
	low	5.35	4.47	3.17
	high	72.57	11.22	18.06

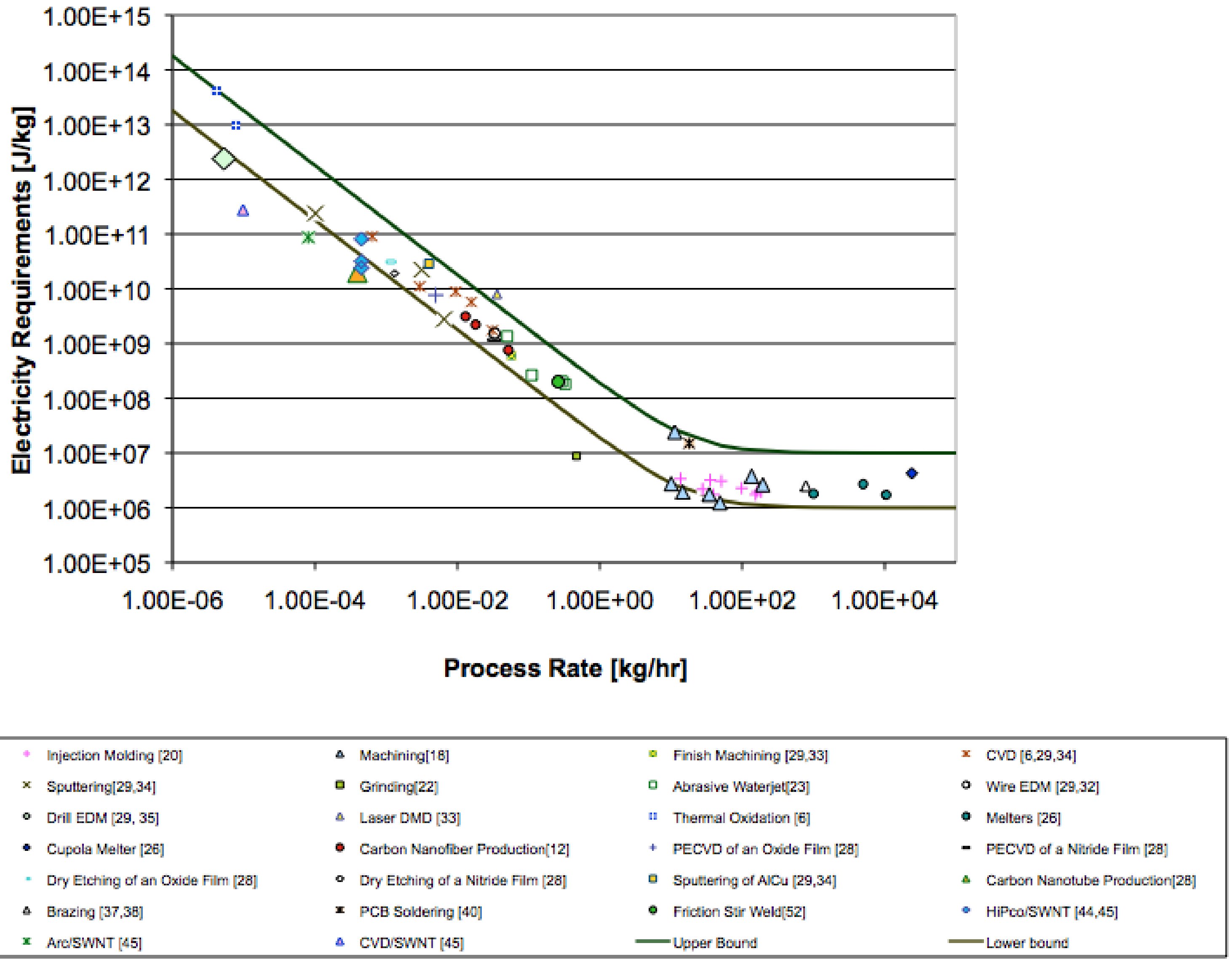
		Hydraulic	Hybrid	All-Electric
TOTAL w/ Generic Inj. Molded Polymer	avg	93.60	87.87	87.20
	low	71.65	70.77	69.46
	high	178.68	117.34	124.18
TOTAL w/o Polymer Prod	avg	18.97	13.24	12.57
	low	8.84	7.96	6.66
	high	81.04	19.70	26.54

Notes **Drying** - the values presented assume no knowledge of the materials' hygroscopia. In order words, they are averages between hygroscopic and non-hygroscopic values. For hygroscopic materials such as PC and PET additional drying energy is needed (0.65 MJ/kg in the case of PC and 0.52 MJ/kg in the case of PET)

Pelletizing - in the case of pelletizing an extra 0.3 MJ/kg is needed for PP

Granulating - a scarp rate of 10 % is assumed

Source: [Thiriez]


Electricity Requirements [J/kg]
1.00E+15
1.00E+14
1.00E+13
1.00E+12
1.00E+11
1.00E+10
1.00E+09
1.00E+08
1.00E+07
1.00E+06
1.00E+05
1.00E-06
1.00E-04
1.00E-02
1.00E+00
1.00E+02
1.00E+04
Process Rate [kg/hr]
Injection Molding [20]
Machining[18]
Finish Machining [29,33]
CVD [6,29,34]
Sputtering[29,34]
Grinding[22]
Abrasive Waterjet[23]
Wire EDM [29,32]
Drill EDM [29, 35]
Laser DMD [33]
Thermal Oxidation [6]
Melters [26]
Cupola Melter [26]
Carbon Nanofiber Production[12]
PECVD of an Oxide Film [28]
PECVD of a Nitride Film [28]
Dry Etching of an Oxide Film [28]
Dry Etching of a Nitride Film [28]
Sputtering of AlCu [29,34]
Carbon Nanotube Production[28]
Brazing [37,38]
PCB Soldering [40]
Friction Stir Weld[52]
HiPco/SWNT [44,45]
Arc/SWNT [45]
CVD/SWNT [45]
Upper Bound
Lower bound

Energy Production Industry

United States Electricity Composition by Source						
Hydro	Nuclear	Other	Coal	Oil	Gas	Waste/ Renewable
7.1%	19.6%	0.0%	50.7%	3.1%	16.7%	2.2%

The Grid is about 30% efficient

For every MJ of electricity we also get:

→171.94 g of CO_2

→0.76 g of SO_2

→ 0.31 g of NO_x

→ 6.24 g of CH_4

→ 0.0032 mg of Hg

Scale

HDPE, LDPE, LLDPE, PP, PS, PVC

Compounder and Injection Molder	U.S. GJ/year	Global GJ/year
6 Main Thermoplastics	9.34E+07	4.01E+08
All Plastics	2.06E+08	6.68E+08

The Injection Molding Industry in the U.S. consumes 6.19 x 10^7 GJ of electricity (or 2.06 x 10^8 GJ in total energy).

This is larger than the entire electric production of some small countries.

In such a scale imagine what a 0.1 % energy savings mean !!!

Do Polymers get recycled?

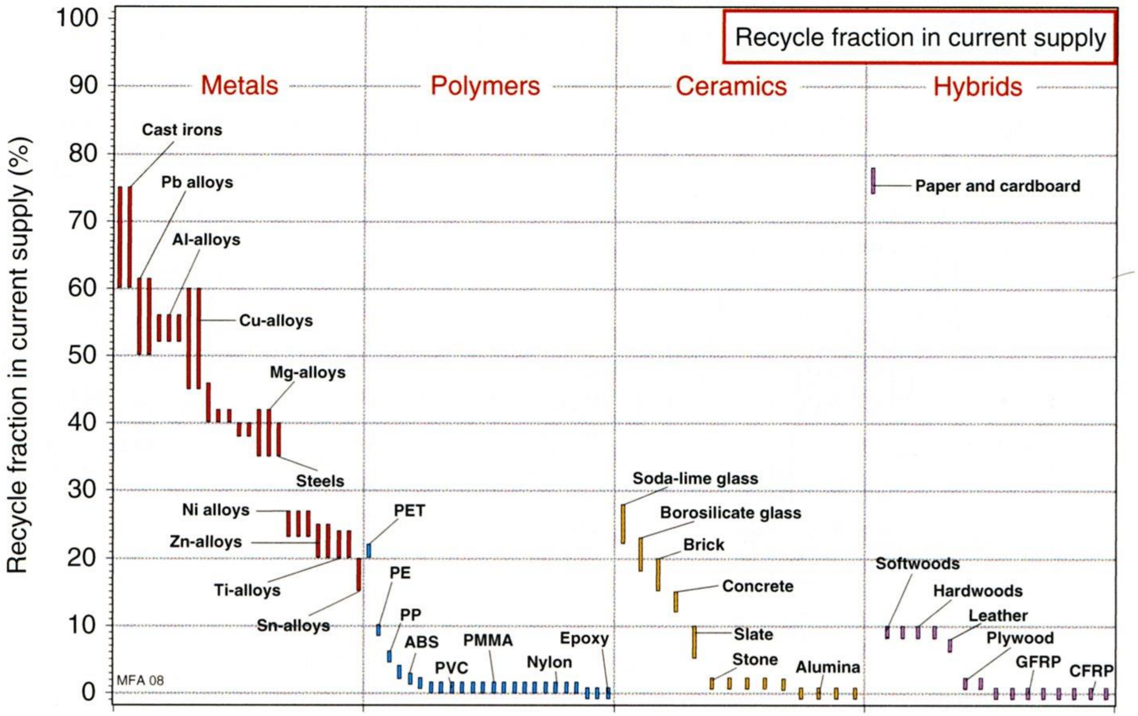


FIGURE 6.13 *Recycle fraction bar chart.*

Ref Ashby 2009

The printer goes in the hopper…

And comes out….

Readings

- Tadmore and Gogos
  - Molding and Casting pp 584 -610
- Boothroyd Dewhurst
  - Design for Injection Molding pp 319 - 359
- Kalpakjian Ch 7 & 19
- Thiriez et al, "An Environmental Analysis of Injection Molding"
- "Injection Molding Case Study" (Gas Assist)