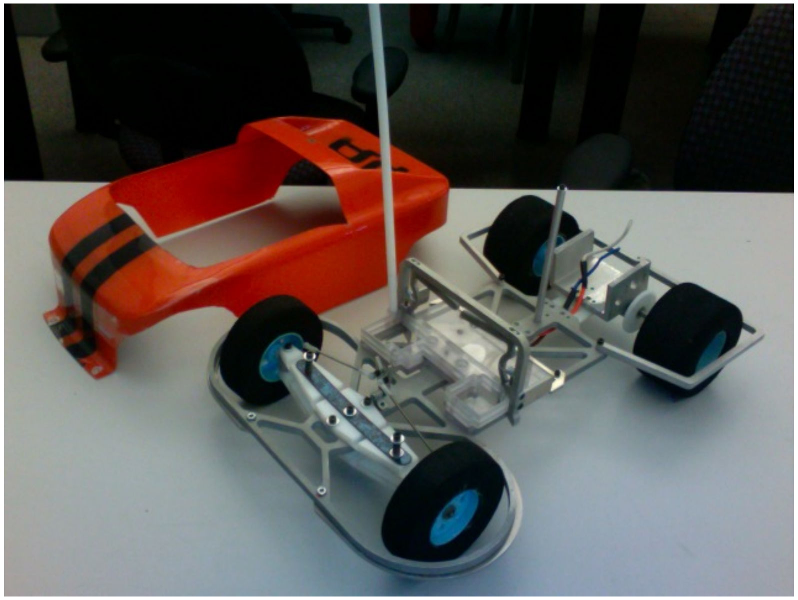


Casting

2.810
T. Gutowski

Casting since about 3200 BCE…

Etruscan casting with runners
circa 500 BCE

China circa 3000BCE

Lost wax jewelry from Greece
circa 300 BCE

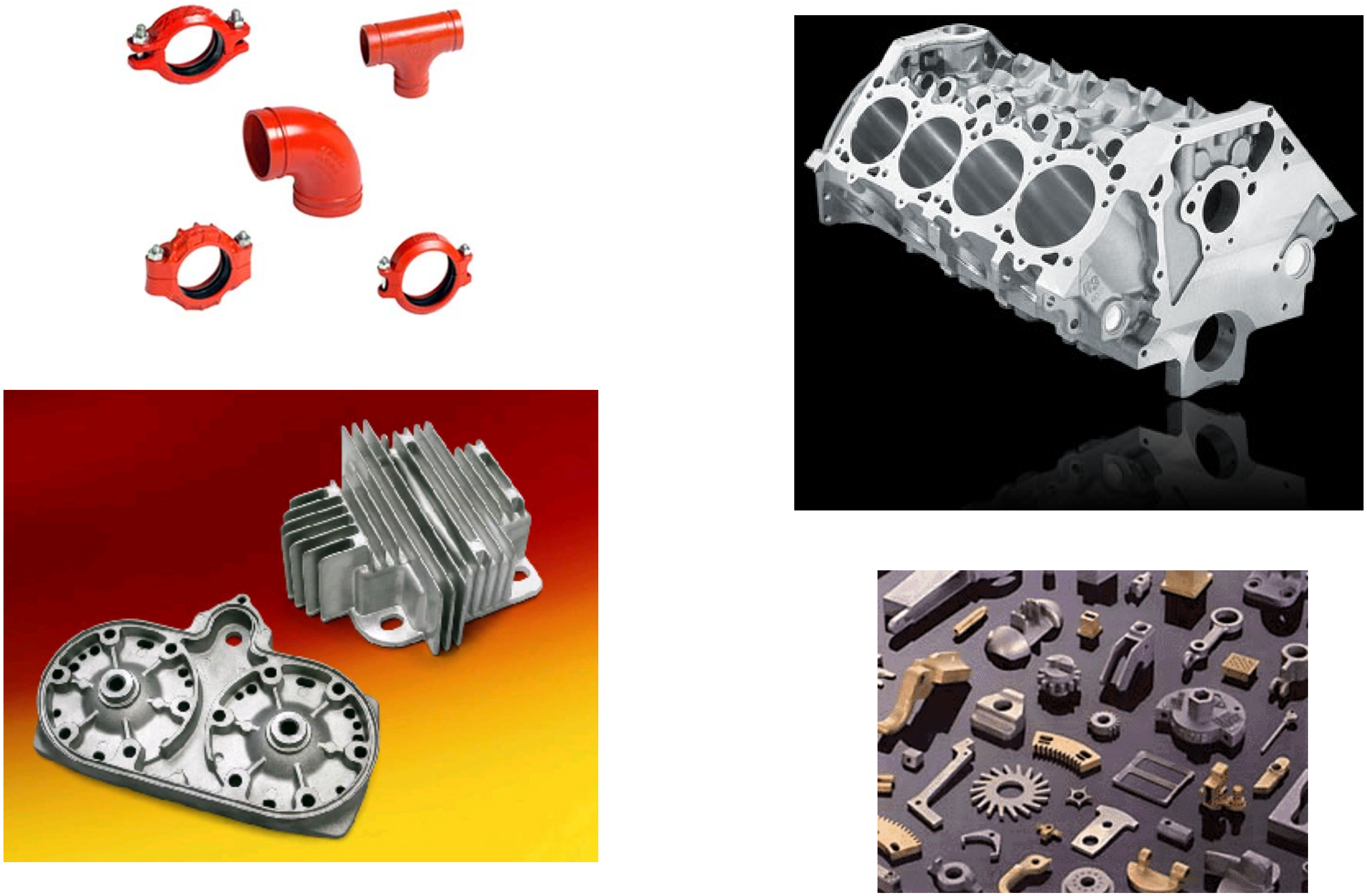
Bronze age to iron age

Bronze statue of Zeus from Artemision,
ca. 460 BC

Ancient Greece; bronze statue casting circa 450BCE

Iron works in early Europe, e.g. cast iron cannons from England circa 1543

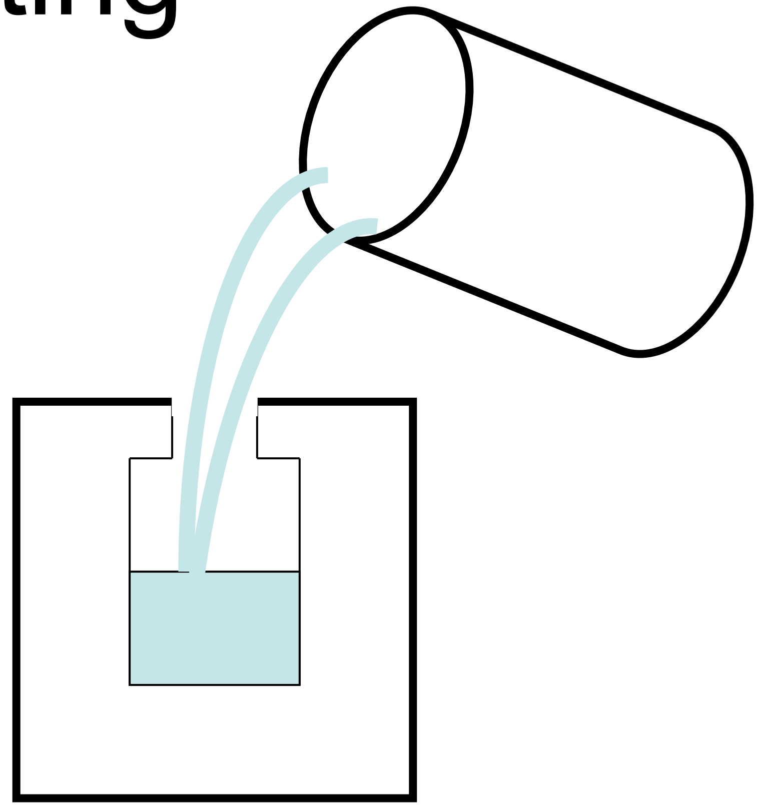
Cast Parts



Outline

1. Review:Sand Casting, Investment Casting, Die Casting
2. Basics: Phase Change, Shrinkage, Heat Transfer
3. Pattern Design and New Technologies
4. Environmental Issues

Casting



Readings;

1. *Kalpakjian, Chapters 10, 11, 12*
2. *Booothroyd, "Design for Die Casting"*
3. *Flemings "Heat Flow in Solidification"*
4. *Dalquist "LCA of Casting"*

Note: a good heat transfer reference can be found by
Profs John Lienhard online http://web.mit.edu/lienhard/www/ahtt.html

Casting Methods

- Sand Casting

High Temperature Alloy,
Complex Geometry,
Rough Surface Finish

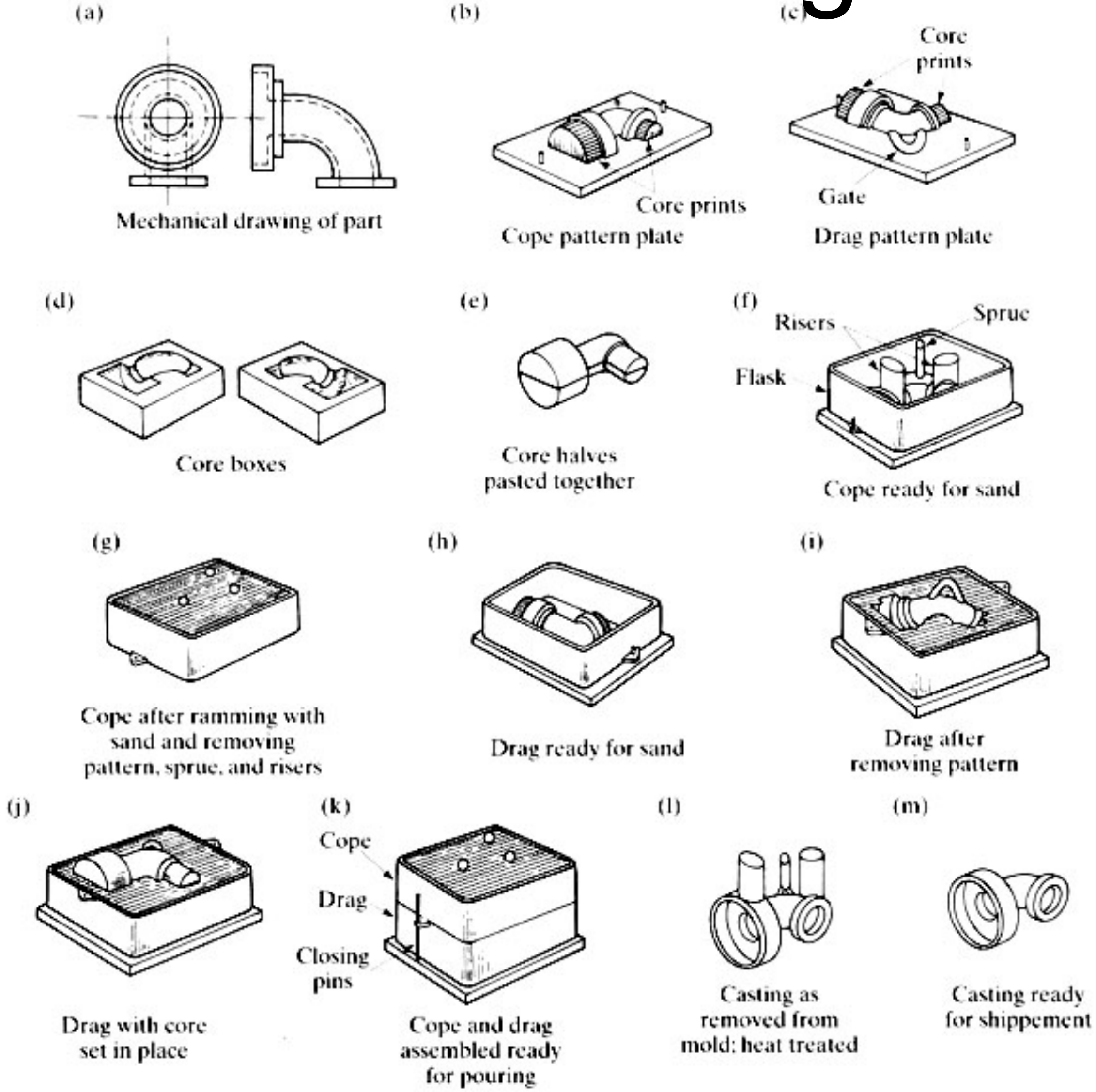
- Investment Casting

High Temperature Alloy,
Complex Geometry,
Moderately Smooth Surface Finish

- Die Casting

High Temperature Alloy,
Moderate Geometry,
Smooth Surface

Sand Casting



(a) Mechanical drawing of part

(b) Cope pattern plate

(c) Drag pattern plate

(d) Core boxes

(e) Core halves pasted together

(f) Cope ready for sand

(g) Cope after ramming with sand and removing pattern, sprue, and risers

(h) Drag ready for sand

(i) Drag after removing pattern

(j) Drag with core set in place

(k) Cope and drag assembled ready for pouring

(l) Casting as removed from mold: heat treated

(m) Casting ready for shippement

Sand Casting

Description: Tempered sand is packed into wood or metal pattern halves, removed form the pattern, and assembled with or without cores, and metal is poured into resultant cavities. Various core materials can be used. Molds are broken to remove castings. Specialized binders now in use can improve tolerances and surface finish.

Metals: Most castable metals.

Size Range: Limitation depends on foundry capabilities. Ounces to many tons.

Tolerances:
  Non-Ferrous ± 1/32″ to 6″
  Add ± .003″ to 3″, ± 3/64″ from 3″ to 6″.
  Across parting line add ± .020″ to ± .090″ depending on size.
  (Assumes metal patterns)

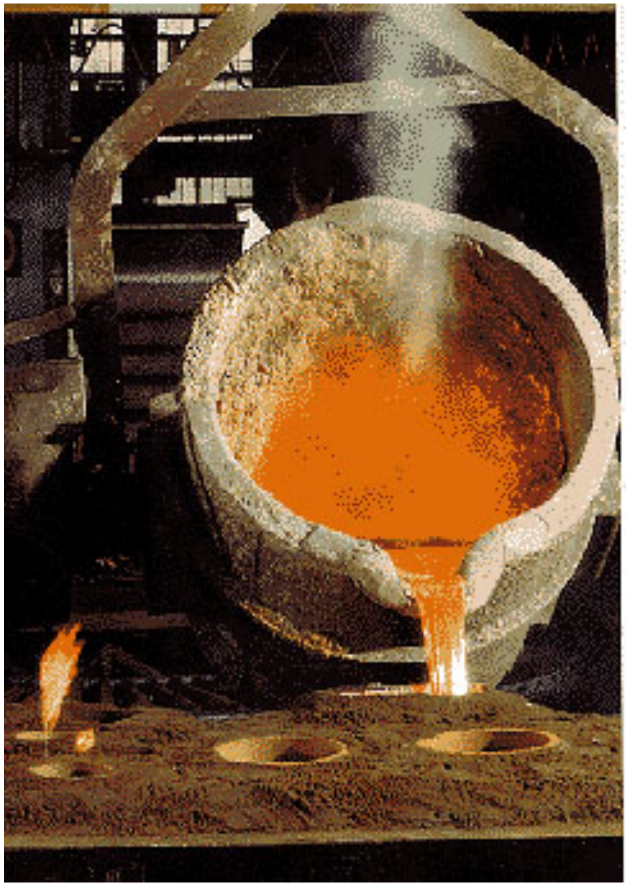
Surface Finish:
  Non-Ferrous: 150-350 RMS
  Ferrous: 300-700RMS

Minimum Draft Requirements:
  1° to 5°
  Cores: 1° to 1 1/2°

Normal Minimum Section Thickness:
  Non-Ferrous: 1/8″ - 1/4″
  Ferrous: 1/4″ - 3/8″

Ordering Quantities: All quantities

Normal Lead Time:
  Samples: 2-10 weeks
  Production 2-4 weeks A.S.A.



Sand Casting Mold Features

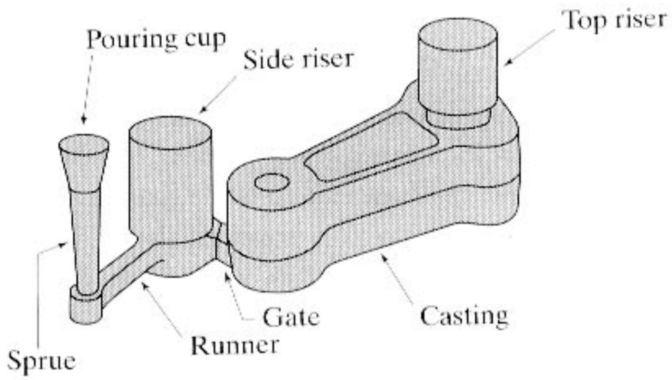


FIGURE 10.7 Schematic illustration of a typical riser-gated casting. Risers serve as reservoirs, supplying molten metal to the casting as it shrinks during solidification. See also Fig. 11.4. *Source*: American Foundrymen's Society.

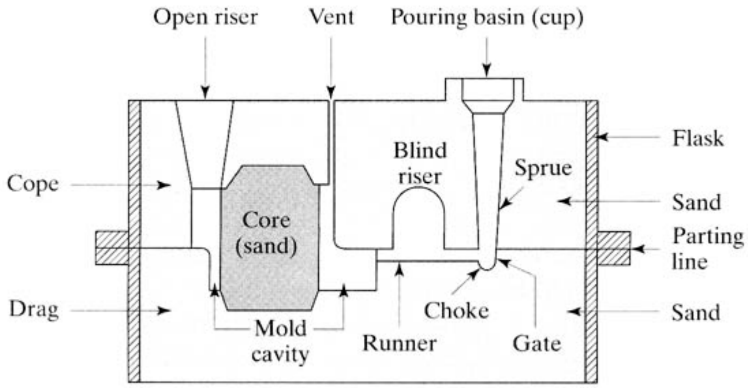


FIGURE 11.4 Schematic illustration of a sand mold, showing various features.

Vents, which are placed in molds to carry off gases produced when the molten metal comes into contact with the sand in the molds and core. They also exhaust air from the mold cavity as the molten metal flows into the mold.

Videos from Mass & Burlington Foundries

Production sand casting

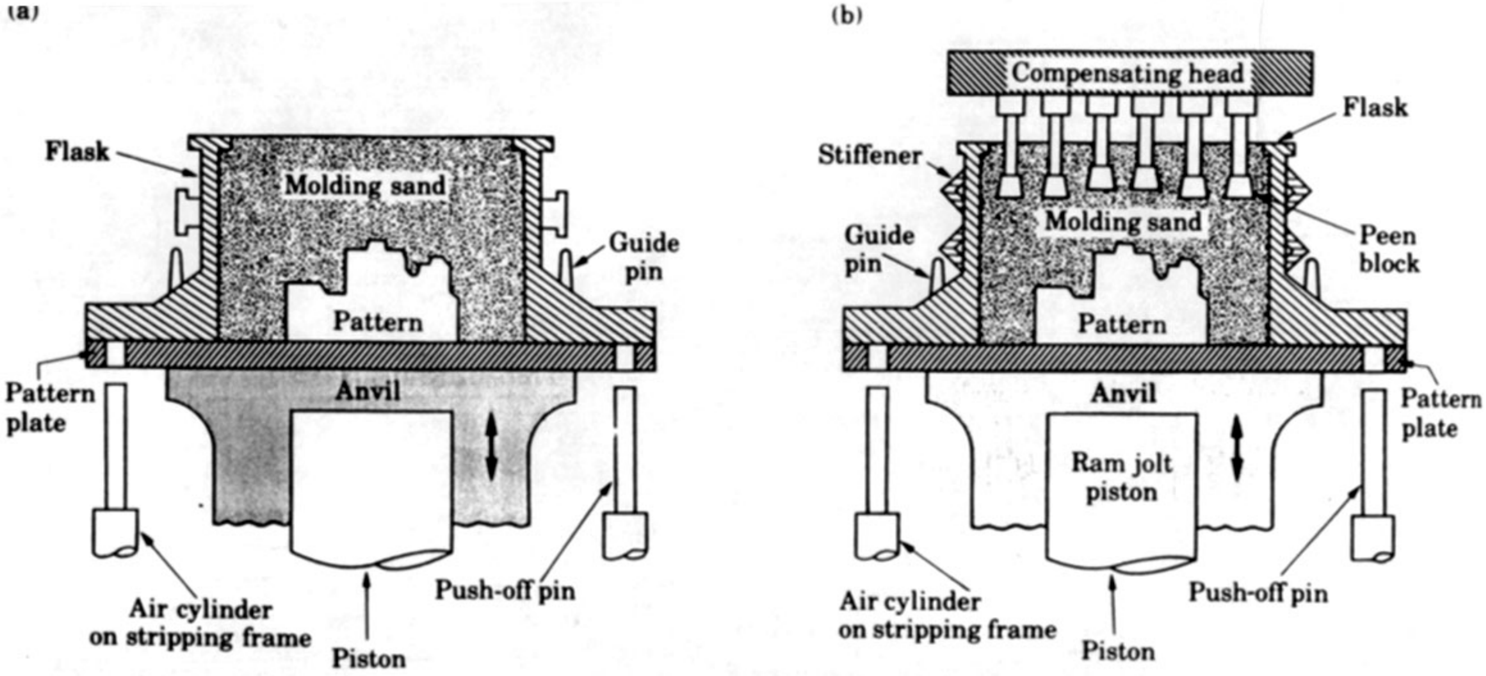


FIGURE 11.8

(a) Schematic illustration of a jolt-type mold-making machine. (b) Schematic illustration of a mold-making machine which combines jolting and squeezing.

Investment Casting

Description: Metal mold makes wax or plastic replica. There are sprued, then surrounded with investment material, baked out, and metal is poured in the resultant cavity. Molds are broken to remove the castings.

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

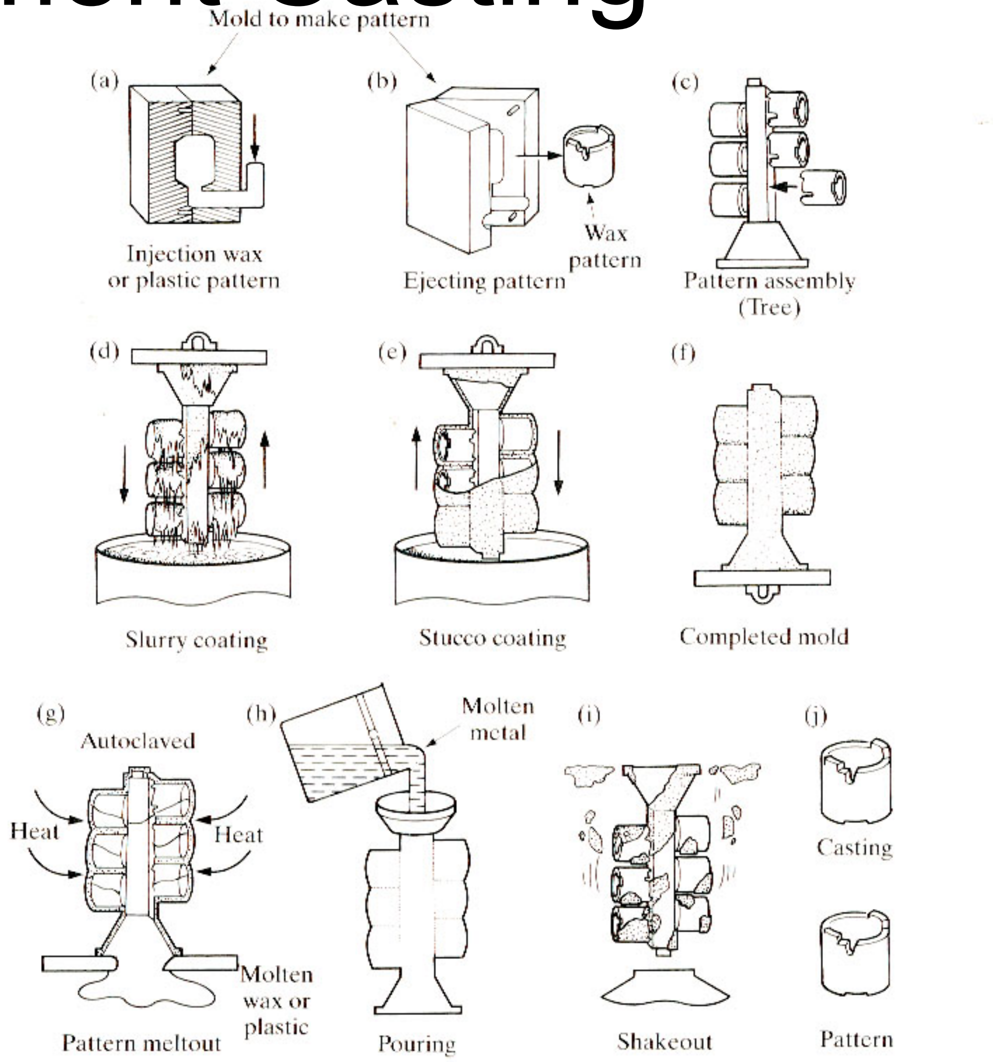
Normal Lead Time:
Samples: 5-16 weeks (depending on complexity)
Production 4-12 weeks A.S.A. (depending on subsequent operations).

Talbot Associates Inc.

Investment Casting

The **investment-casting process**, also called the *lost-wax* process, was first used during the period 4000-3500 B.C. The pattern is made of wax or a plastic such as polystyrene. The sequences involved in investment casting are shown in Figure 11.18. The pattern is made by injecting molten wax or plastic into a metal die in the shape of the object.

FIGURE 11.18 Schematic illustration of investment casting (lost-wax process). Castings by this method can be made with very fine detail and from a variety of metals. *Source*: Steel Founders' Society of America.



Die Casting

Description: Molten metal is injected, under pressure, into hardened steel dies, often water cooled. Dies are opened, and castings are ejected.

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

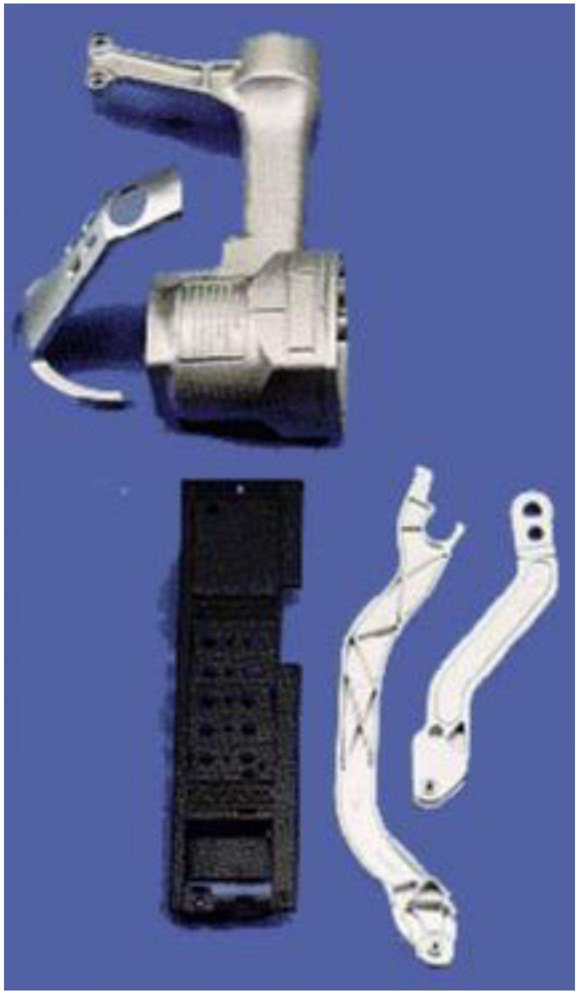
Surface Finish: 32-63RMS

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

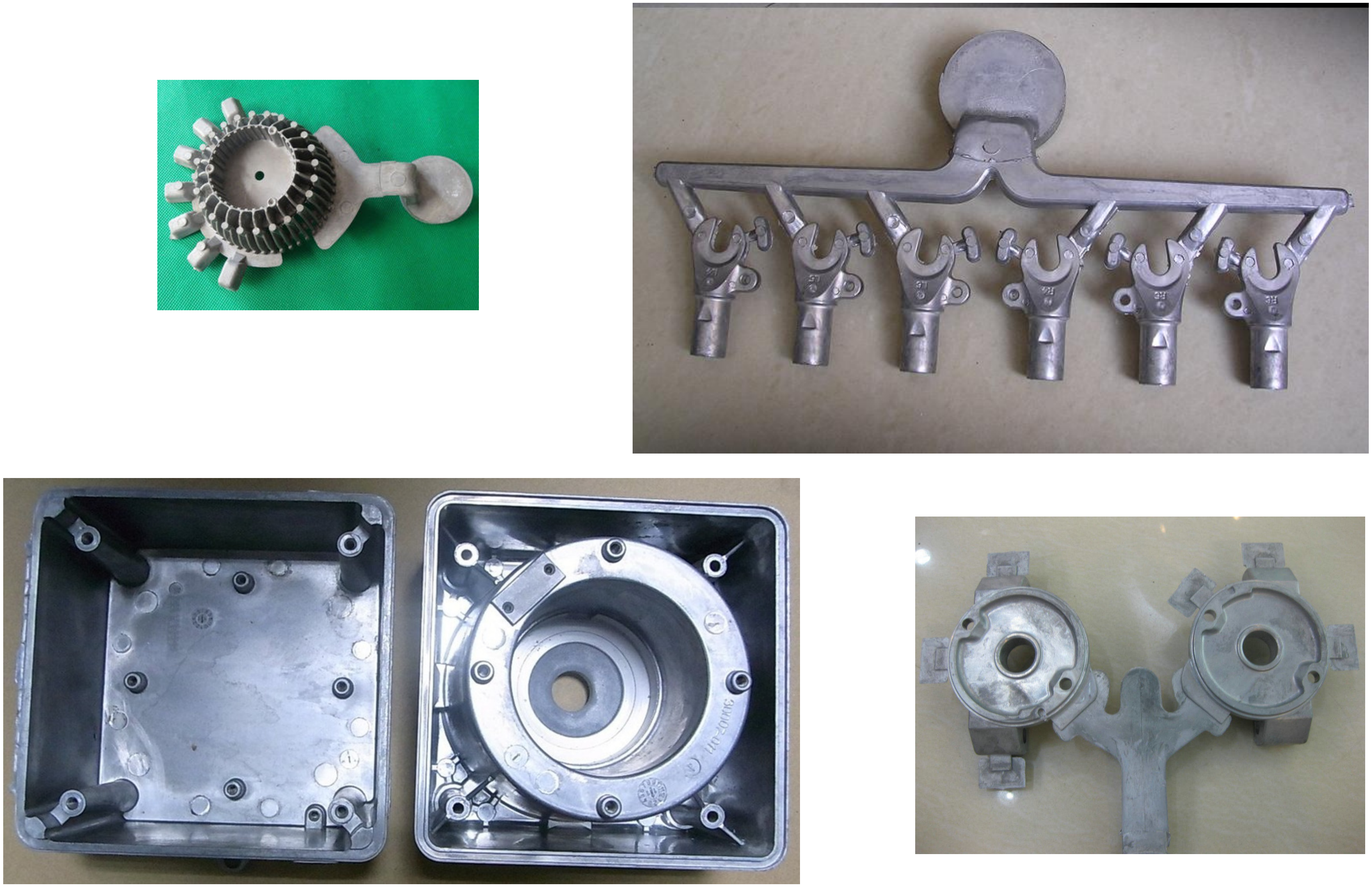
Normal Minimum Section Thickness:
  Al & Mg: .03″ Small Parts: .06″ Medium Parts
  Zinc: .03″ Small Parts: .045″ Medium Parts
  Brass: .025″ Small Parts: .040″ Medium Parts

Ordering Quantities:
  Usually 2,500 and up.

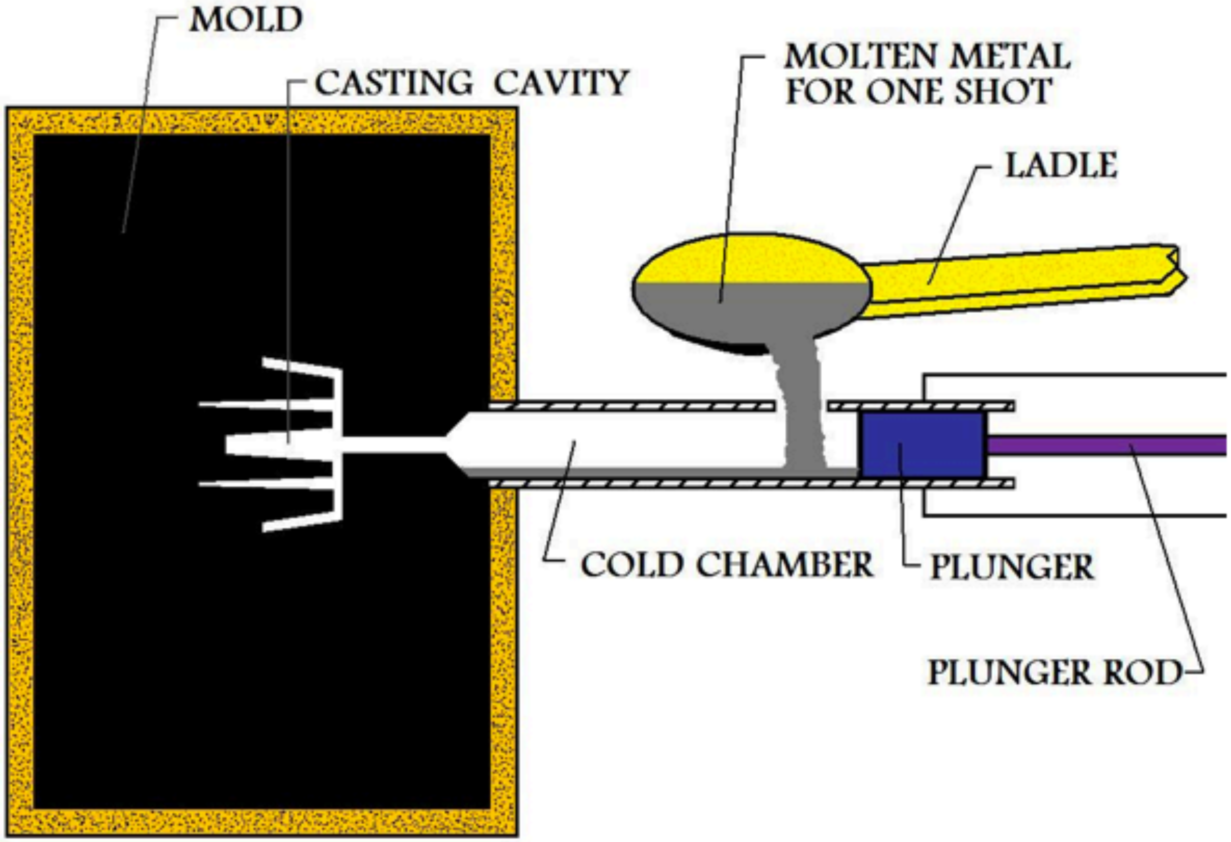
Normal Lead Time:
  Samples: 12-20 weeks
  Production: ASAP after approval.



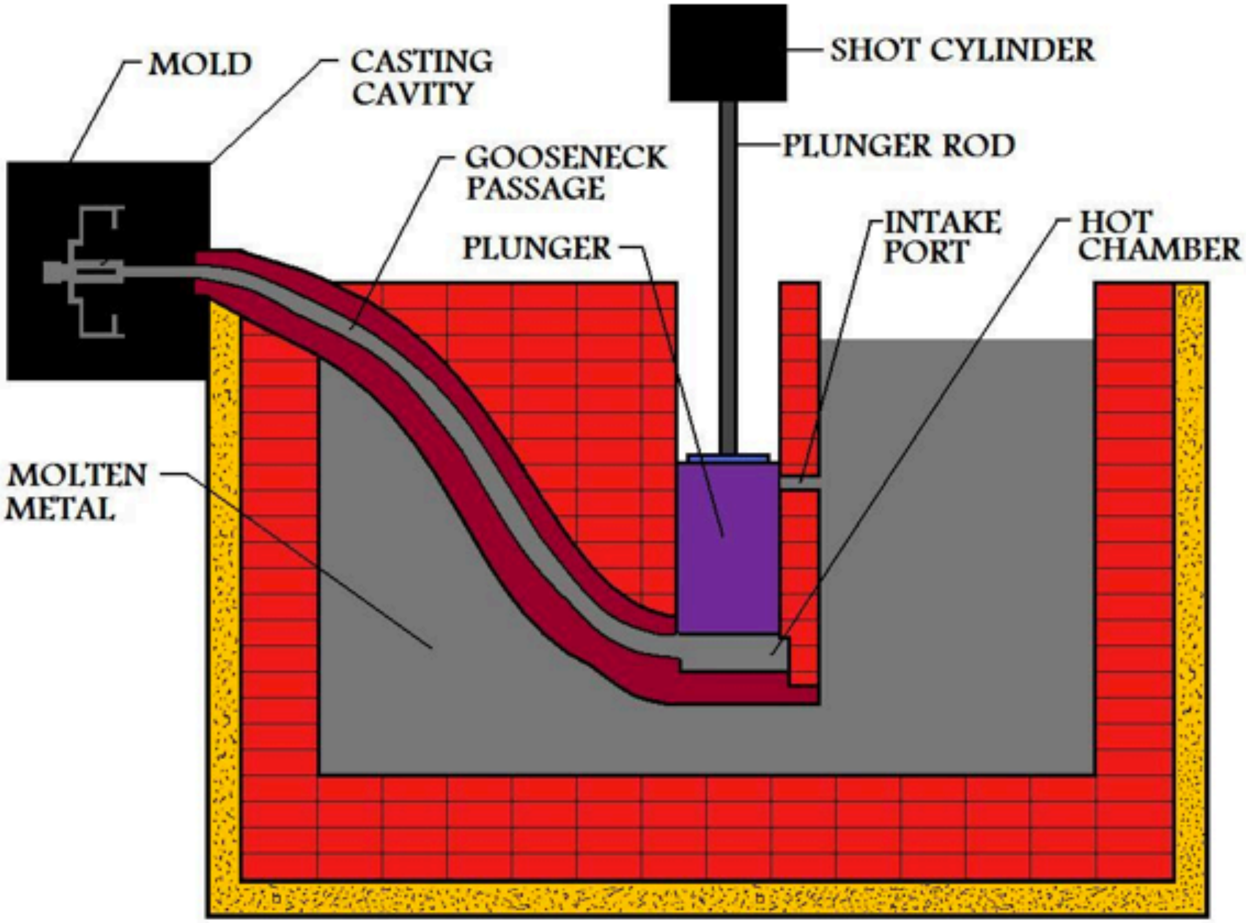
Die cast parts & runners



COLD CHAMBER DIE CASTING



http://thelibraryofmanufacturing.com

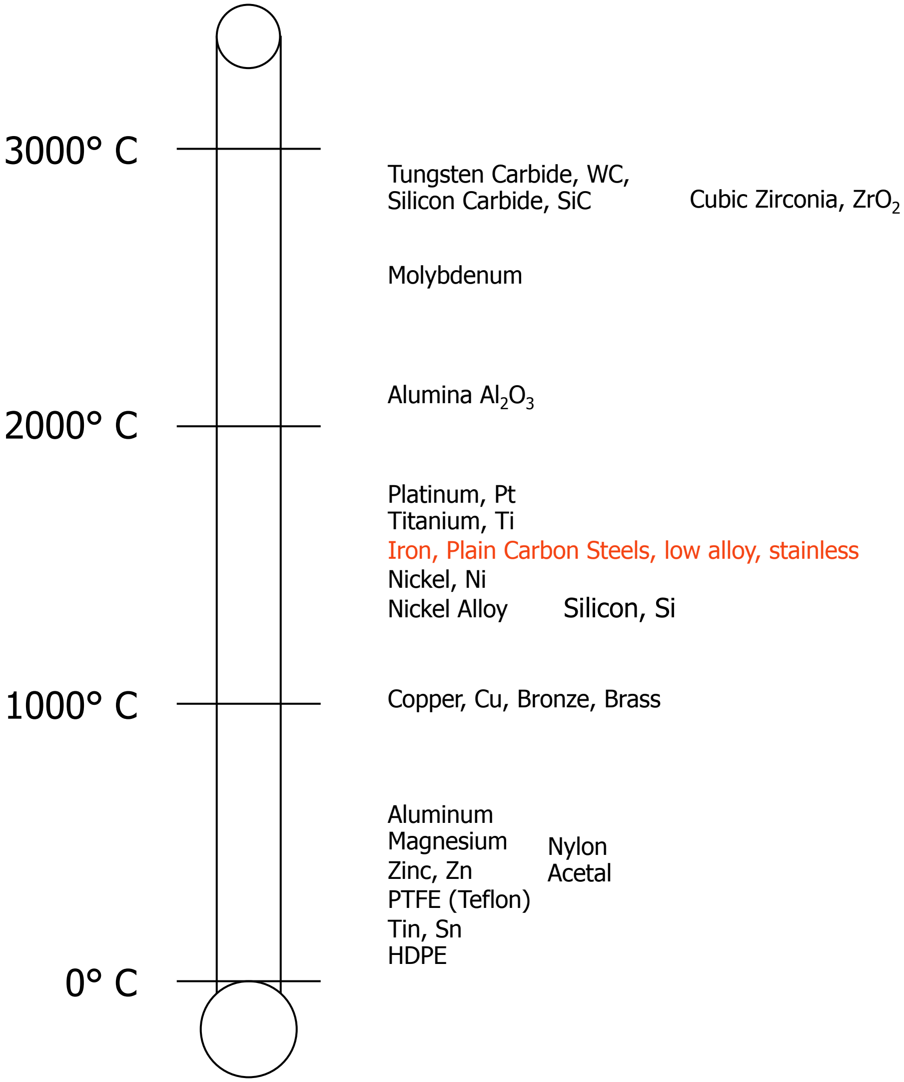


HOT CHAMBER DIE CASTING

http://thelibraryofmanufacturing.com

High Melt Temperature

- Reactivity
  - with air, mold mat’ ls,
- Gas solubility
  - H_2 gas in Al
- Safety
  - Metal fires, e.g. Mg



3000° C

Tungsten Carbide, WC,
Silicon Carbide, SiC

Cubic Zirconia, ZrO_2

Molybdenum

Alumina Al_2O_3

2000° C

Platinum, Pt
Titanium, Ti
Iron, Plain Carbon Steels, low alloy, stainless
Nickel, Ni
Nickel Alloy

Silicon, Si

1000° C

Copper, Cu, Bronze, Brass

Aluminum
Magnesium
Zinc, Zn
PTFE (Teflon)
Tin, Sn
HDPE

Nylon
Acetal

0° C

Mold Filling

Bernouli’s Equation:

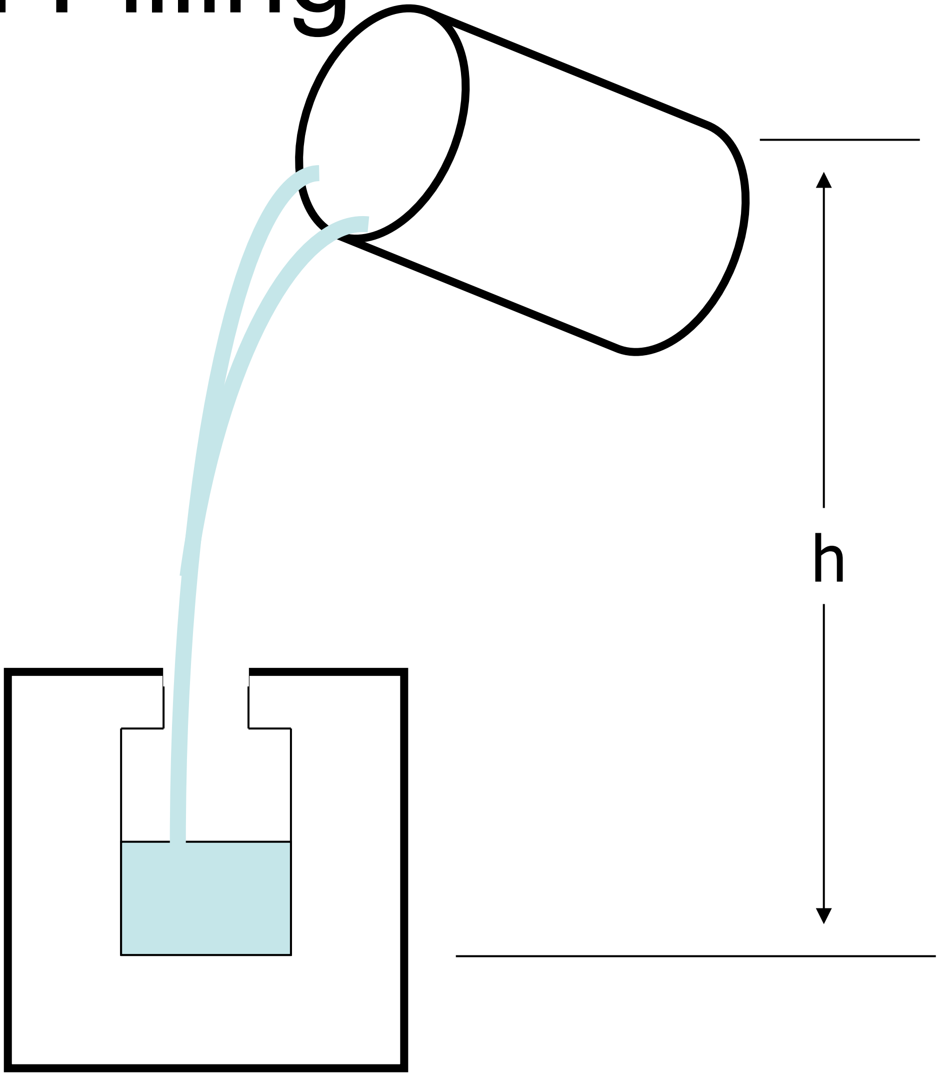
$$h + \frac{p}{pg} + \frac{v^2}{2g} = Const.$$

Reynold’s Number:

$$\text{Re} = \frac{vDP}{\mu}$$

- Short filling times
- Potential Turbulence

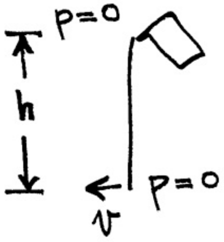
(see Kalpakjian..Ch 10)



Mold Filling Example

Mold Filling Example (order of magnitude)

from Bernoulli's Eq'n the inlet velocity can be estimated as:



$$v \cong \sqrt{2gh}$$

$$= \sqrt{2 \times 10 \frac{m}{s^2} \times 10^{-1} m} = 1.4 \frac{m}{s}$$

estimate Reynold's Number

$$Re = \frac{vD\rho}{\mu} = \frac{1.4 \frac{m}{s} \cdot 0.5cm \cdot 2.7 \frac{g}{cm^3}}{10^{-3} \frac{N}{m^2} \cdot s} = 18,900$$

Mold filling issues: oxidation, turbulence, mold erosion, soluble gases, safety

Phase Change & Shrinkage

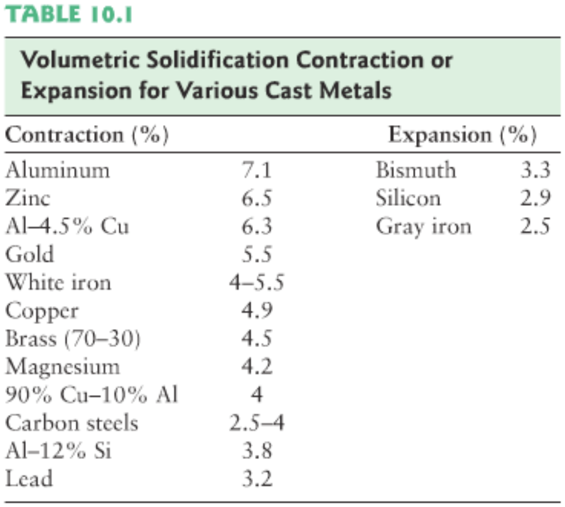
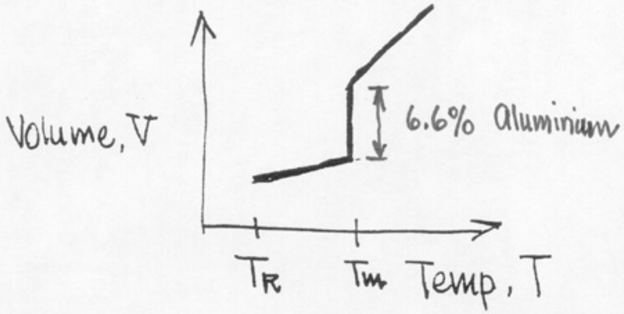
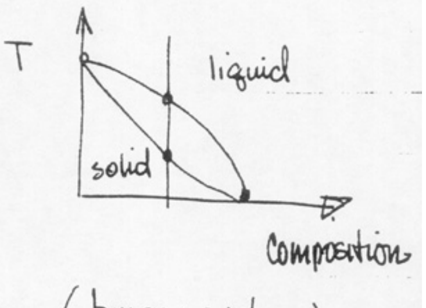


TABLE 10.1

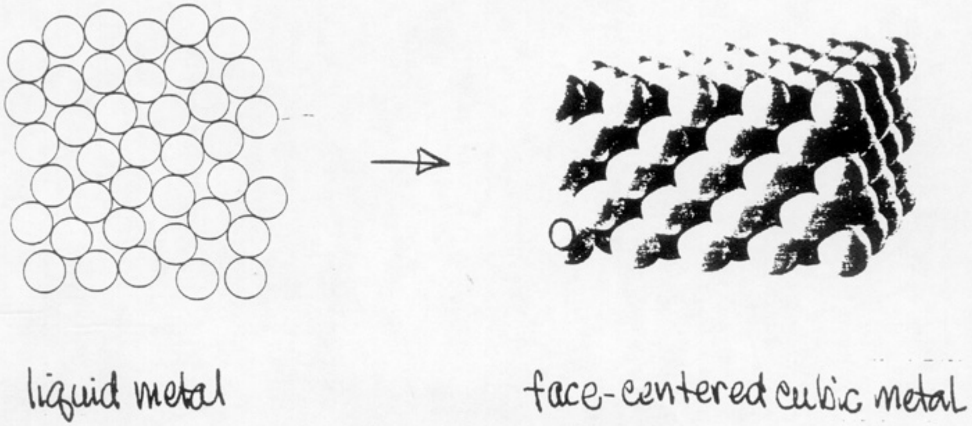
Volumetric Solidification Contraction or Expansion for Various Cast Metals

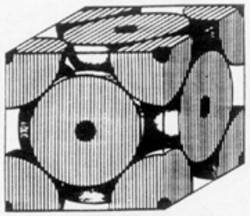
Contraction (%)		Expansion (%)	
Aluminum	7.1	Bismuth	3.3
Zinc	6.5	Silicon	2.9
Al–4.5% Cu	6.3	Gray iron	2.5
Gold	5.5		
White iron	4–5.5		
Copper	4.9		
Brass (70–30)	4.5		
Magnesium	4.2		
90% Cu–10% Al	4		
Carbon steels	2.5–4		
Al–12% Si	3.8		
Lead	3.2		

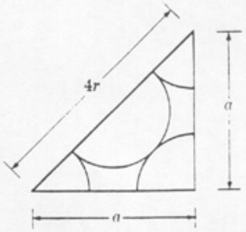




(binary system)







$$a_{fcc} = 4r/\sqrt{2}$$

$$a_{bcc} = 4r/\sqrt{3}$$

Solidification of a binary alloy

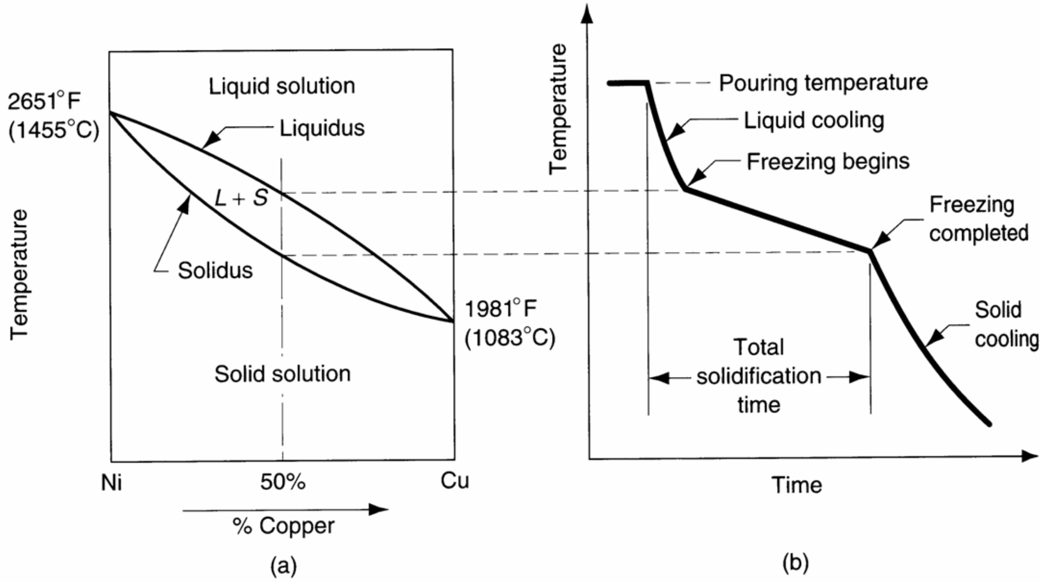


FIGURE 12.5 (a) Phase diagram for a copper–nickel alloy system and (b) associated cooling curve for a 50%Ni–50%Cu composition during casting.

Composition change during solidification

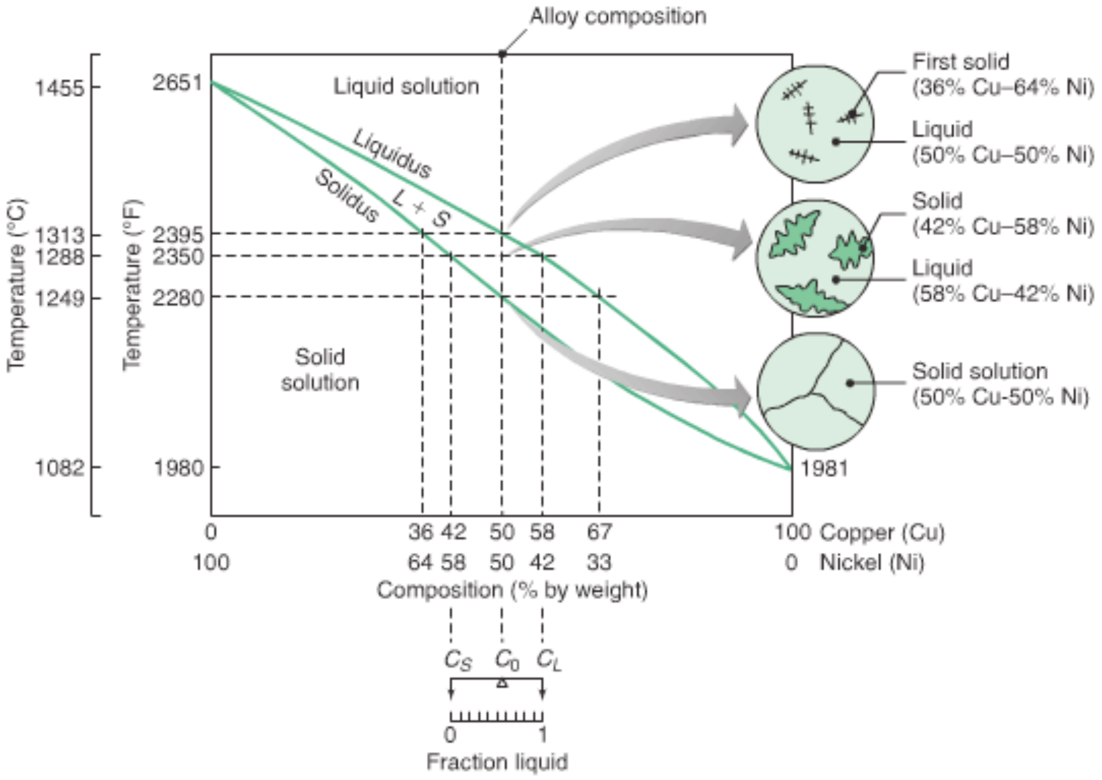


FIGURE 4.5 Phase diagram for nickel–copper alloy system obtained at a slow rate of solidification. Note that pure nickel and pure copper each have one freezing or melting temperature. The top circle on the right depicts the nucleation of crystals. The second circle shows the formation of dendrites (see Section 10.2). The bottom circle shows the solidified alloy, with grain boundaries.

Pb-Sn phase diagram

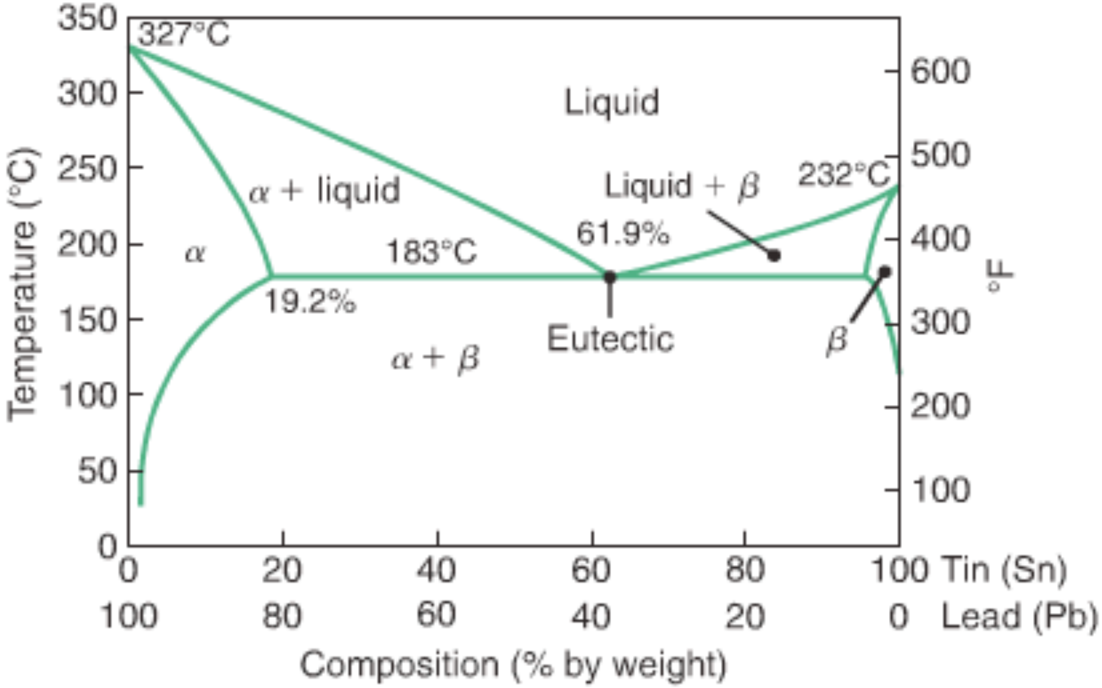


FIGURE 4.7 The lead–tin phase diagram. Note that the composition of the eutectic point for this alloy is 61.9% Sn–38.1% Pb. A composition either lower or higher than this ratio will have a higher liquidus temperature.

Solidification

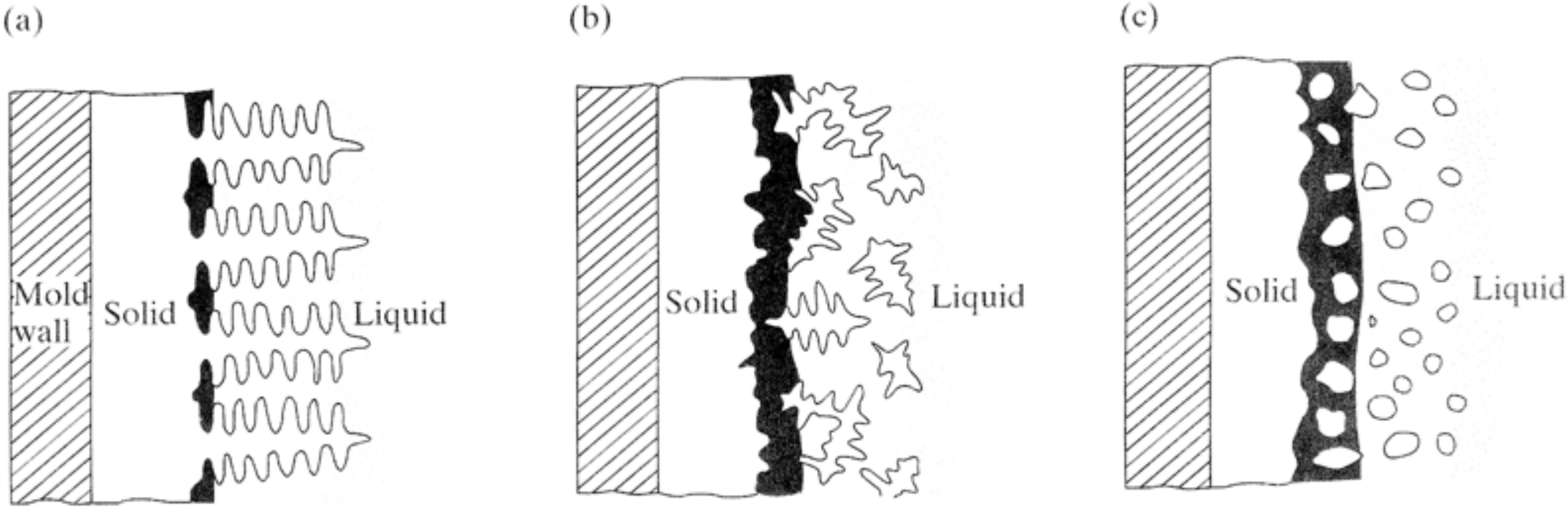
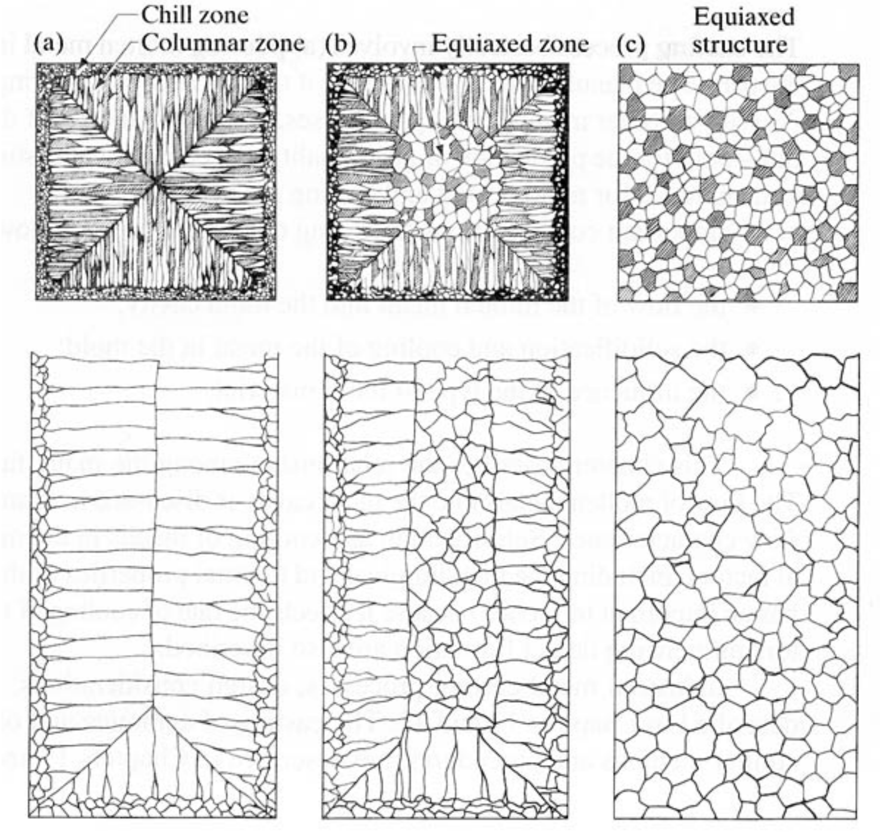


FIGURE 10.5 Schematic illustration of three basic types of cast structures:(a) columnar dendritic; (b) equiaxed dendritic; and (c) equiaxed nondendritic. *Source*: D. Apelian.

http://www.its.caltech.edu/~atomic/snowcrystals/

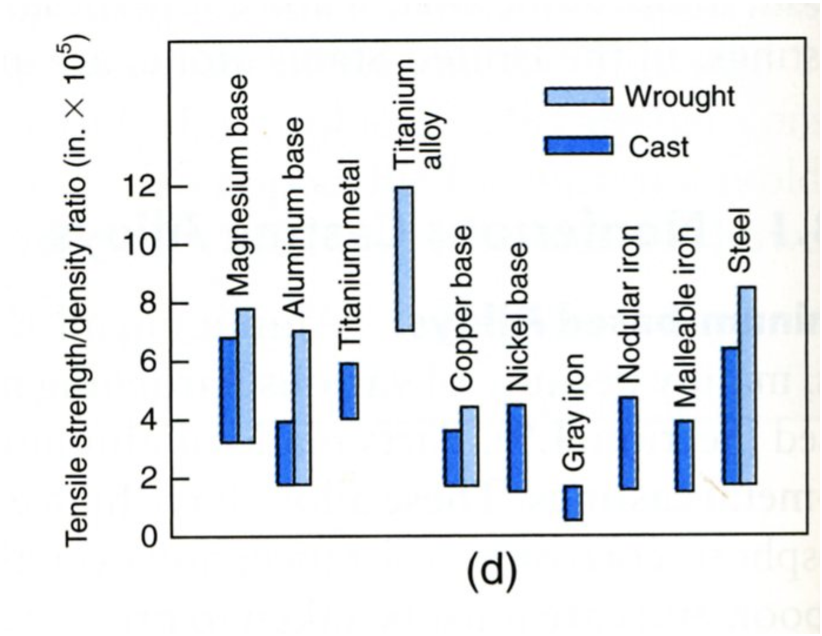
Dendrite growth in metals- lower surface energy crystallographic planes are favored, producing tree like structures if not disturbed.

Cast structures



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

Properties of castings



e.g. Compare elongation of carbon steels (4-36%)Table 5.3, with cast irons (0-18%) Table 12.3 (Kalpakjian & Schmid 7th)

How long does it take to solidify?

Thickness ~ 30 cm

Thickness ~ 0.5 cm

Heat Transfer – Sand Casting

$$t_s \approx \left(\frac{V}{A}\right)^2$$

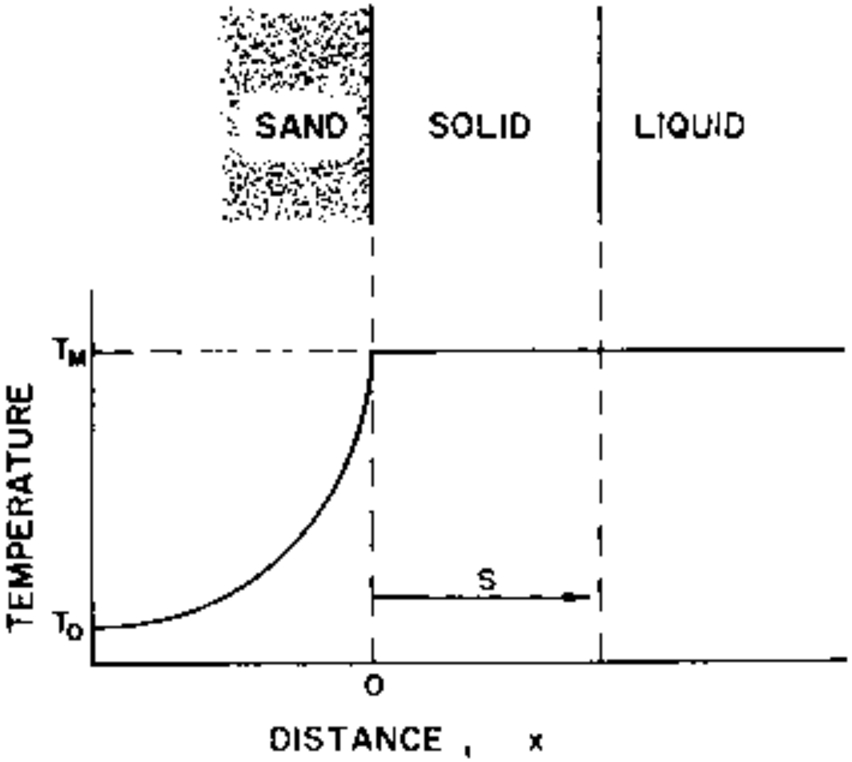


FIGURE 1-6
Approximate temperature profile in solidification of a pure metal poured at its melting point against a flat, smooth mold wall.

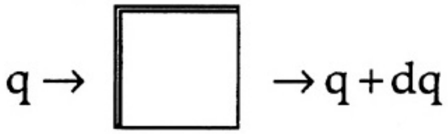
Ref: Mert Flemings "Solidification Processing"

Thermal Conductivity “k” (W/m·K)

$$q = -k\frac{dT}{dx}$$

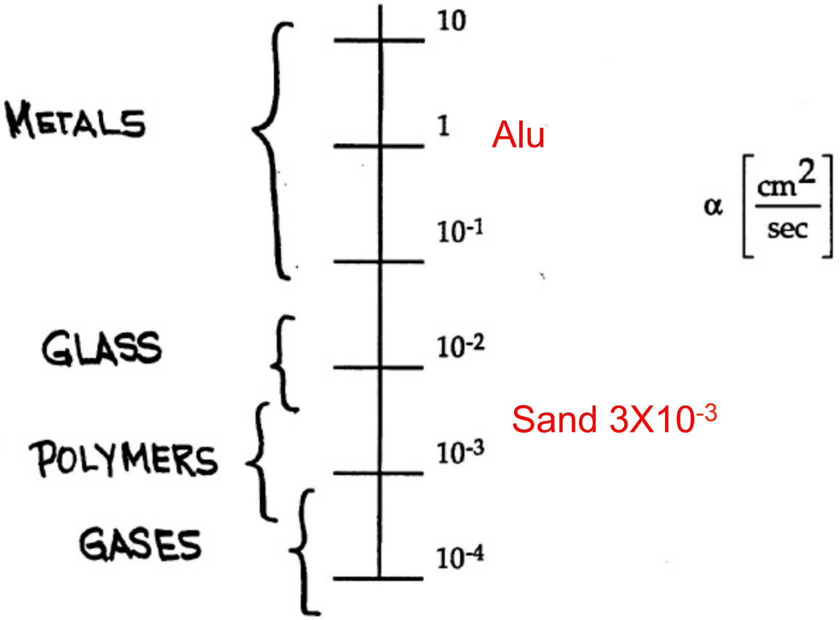
Copper	394
Aluminum	222
Iron	29
Sand	0.61
PMMA	0.20
PVC	0.16

Transient Heat Transfer



$$\boxed{\rho C_p \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial x^2}}$$

$k \neq k(x)$



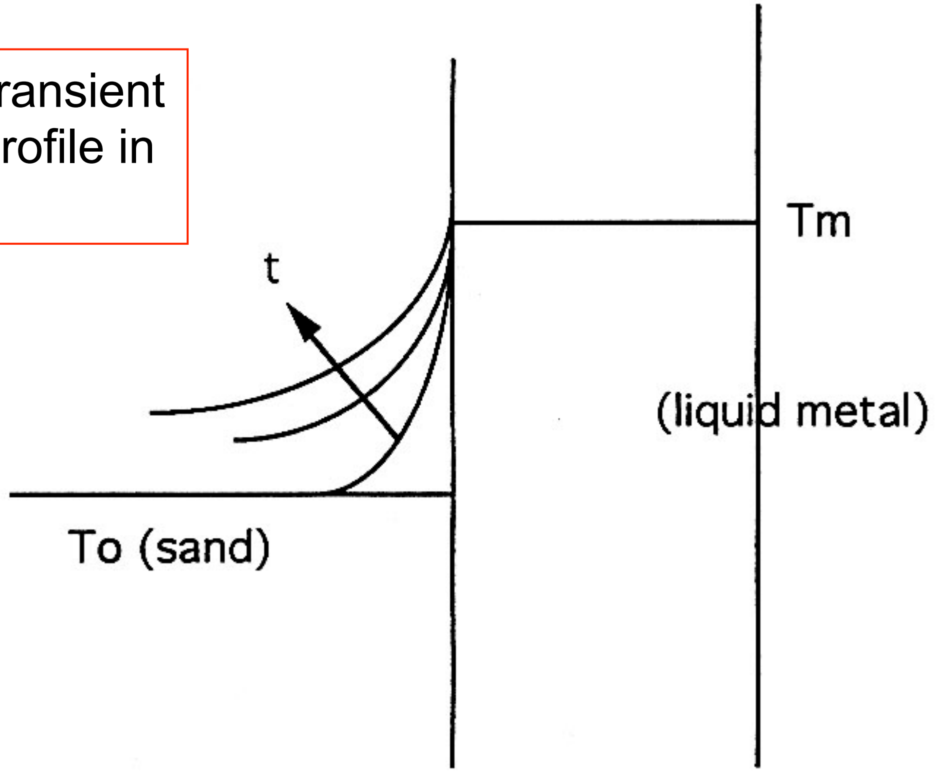
$$\alpha = \frac{k}{\rho C_p}$$

Sand Casting (see Flemings)

Define new variable $\zeta = x / \sqrt{\alpha t}$

Use $\theta = \dfrac{T - T_M}{T_o - T_M}$

We seek the transient temperature profile in the sand.



Sand Casting (see Flemings)

Ordinary differential eq'u

$$\frac{d^2\theta}{d\zeta^2} = -\frac{\zeta}{2}\frac{d\theta}{d\zeta}$$

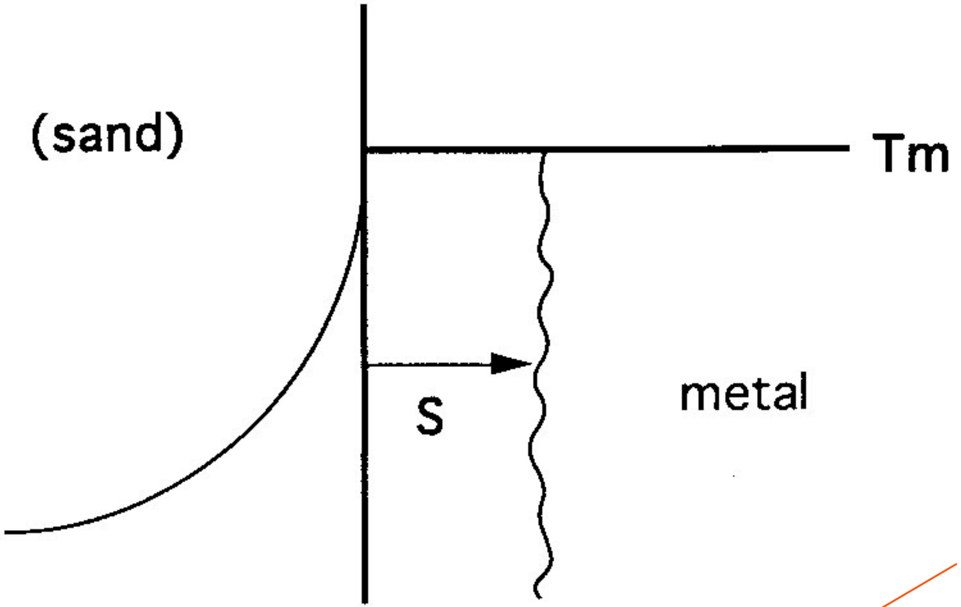
i.c. $\theta = 1$ at $\zeta = \infty$ At t=0, $T=T_o$ everywhere

b.c. $\theta = 0$ at $\zeta = 0$ At x=0, $T=T_m$ always

This will allow us to calculate the heat lost by the metal at the boundary with the sand tooling

$$\boxed{\theta = \operatorname{erf}\left(-\frac{\zeta}{2}\right)}$$

Solidification Time



Enthapy/wt

Heat required to solidify to distance "s"

$$= A \cdot s \cdot \rho \cdot H$$

Use Flemings result here

Rate eq'n (per unit area)

$$\rho H \frac{ds}{dt} = -\dot{q} = k\left(\frac{\partial T}{\partial x}\right)_{x=0}$$

Solidification Time (cont.)

this leads to

$$s = \frac{2}{\sqrt{\pi}}\left(\frac{T_M - T_o}{\rho_M H_M}\right)\sqrt{K_s \rho_s C_{p_s} t}$$

let $s = \frac{V}{A}$

$$\boxed{t = C\left(\frac{V}{A}\right)^2}$$

Chvorinov's rule

The constant “C” (in this case not heat capacity) is determined by experiment.

Several references suggest that values range:

$C \sim 2$ to 4 min/cm^2 (with most data for iron and steel)

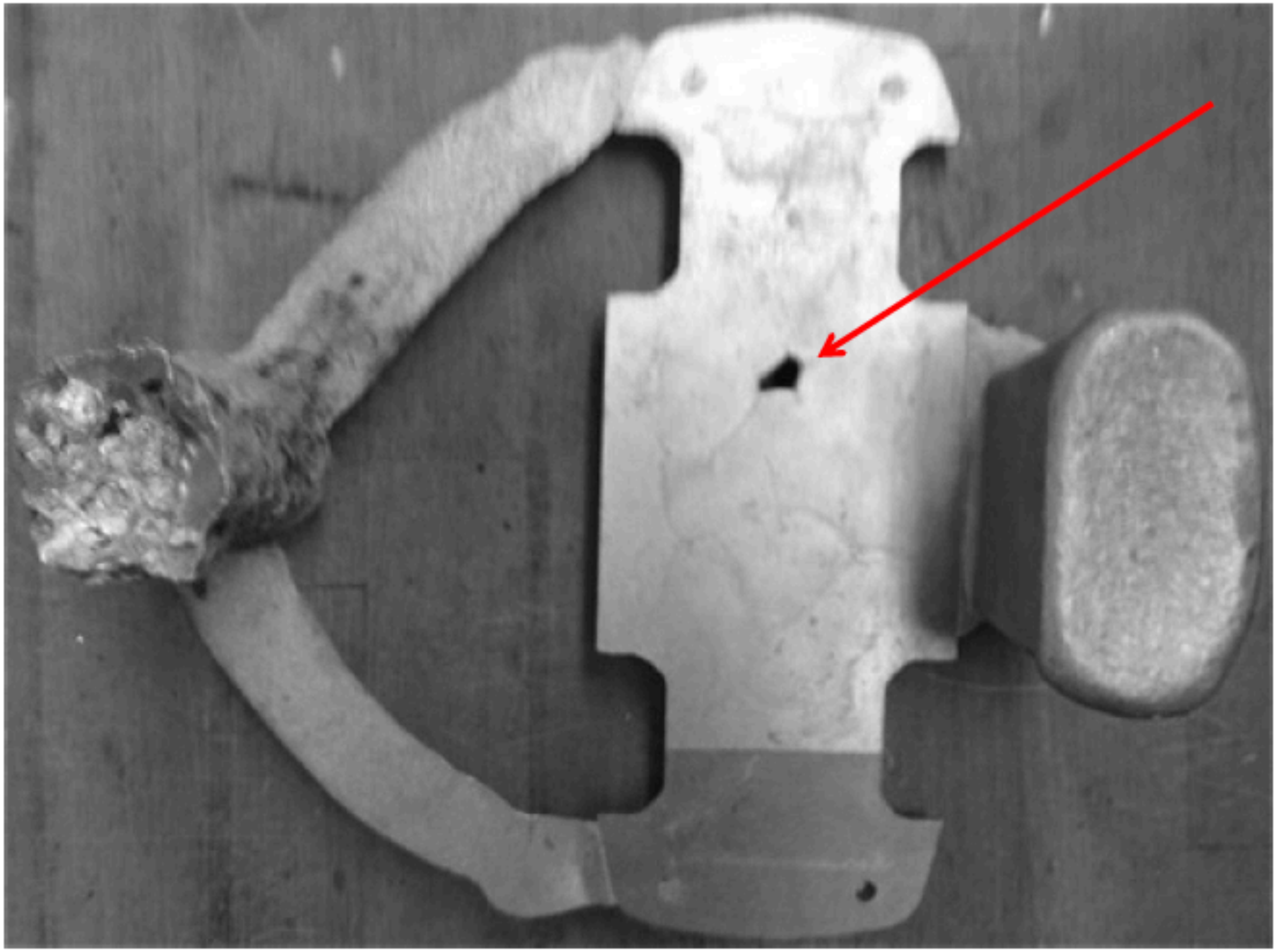
How long does it take to solidify?

Order of magnitude estimate using half thickness, & C = 3.3 min/cm^2

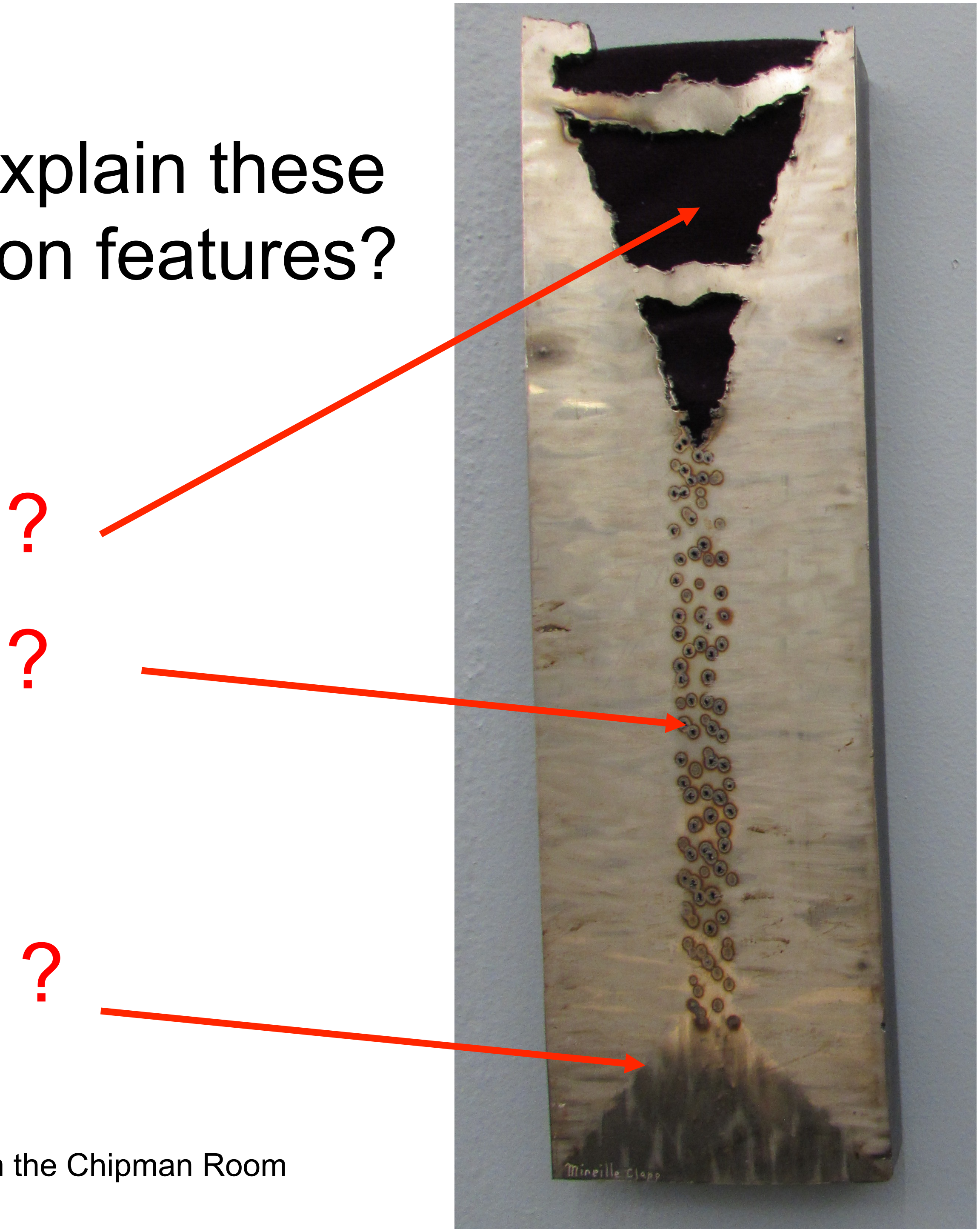
Thickness ~ 30 cm
Solidification time = 3.3 $(30/2)^2$ [min] ~ 12 hrs

Thickness ~ 0.5 cm
t = 3.3 $(0.5/2)^2$ [min] ~ 12 sec

What happened?



Can you explain these Solidification features?



Picture taken from the Chipman Room

Pattern Design suggestions

Figure 7.2.24 Identifying hot spots in castings by using outward projecting arrows of length half the casting thickness. Where arrows overlap, hot spots may develop. (Courtesy of Meehanite Metal Corp.)

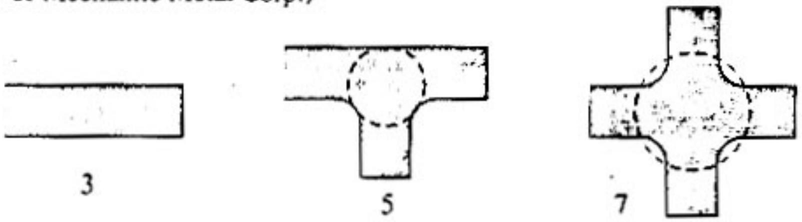


Figure 7.2.25 Examples of relative cooling times. (Courtesy of Meehanite Metal Corp.)

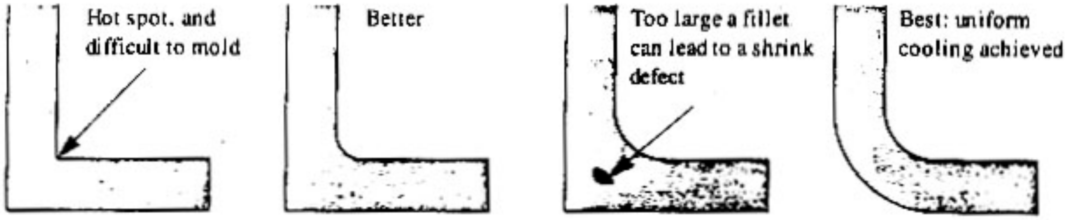


Figure 7.2.26 Fillet all sharp angles. (Courtesy of Meehanite Metal Corp.)

More Pattern Design suggestions

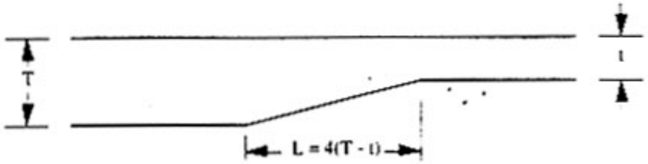


Figure 7.2.28 Avoid abrupt section changes. (Courtesy of Meehanite Metal Corp.)

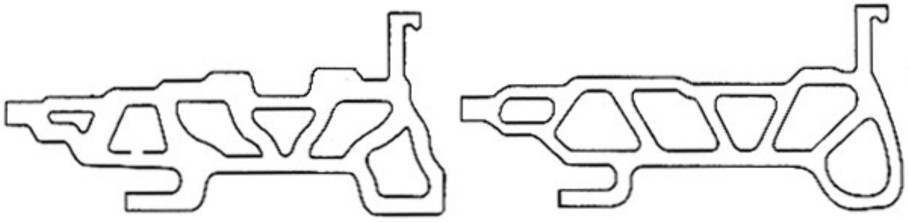


Figure 7.2.29 Design for uniform thickness in sections. (Courtesy of Meehanite Metal Corp.)

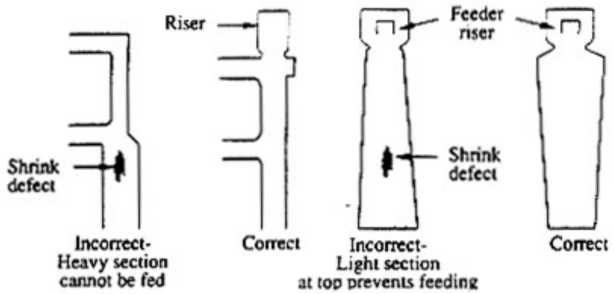


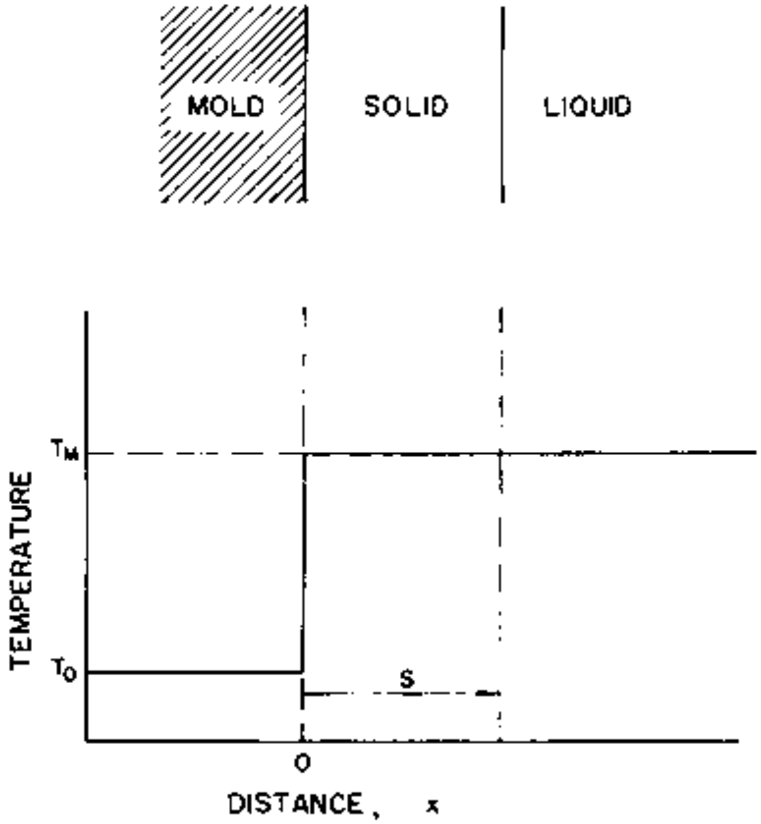
Figure 7.2.30 More intersection details. (Courtesy of Meehanite Metal Corp.)

Figure 7.2.31 Design for bolting or bearing bosses. (Courtesy of Meehanite Metal Corp.)

Heat Transfer – Die Casting

$$t_s \approx \left(\frac{V}{A}\right)^1$$

FIGURE 1-9
Temperature profile during solidification against a large flat mold wall with mold-metal interface resistance controlling.



Film Coefficients "h" W/m^2·K

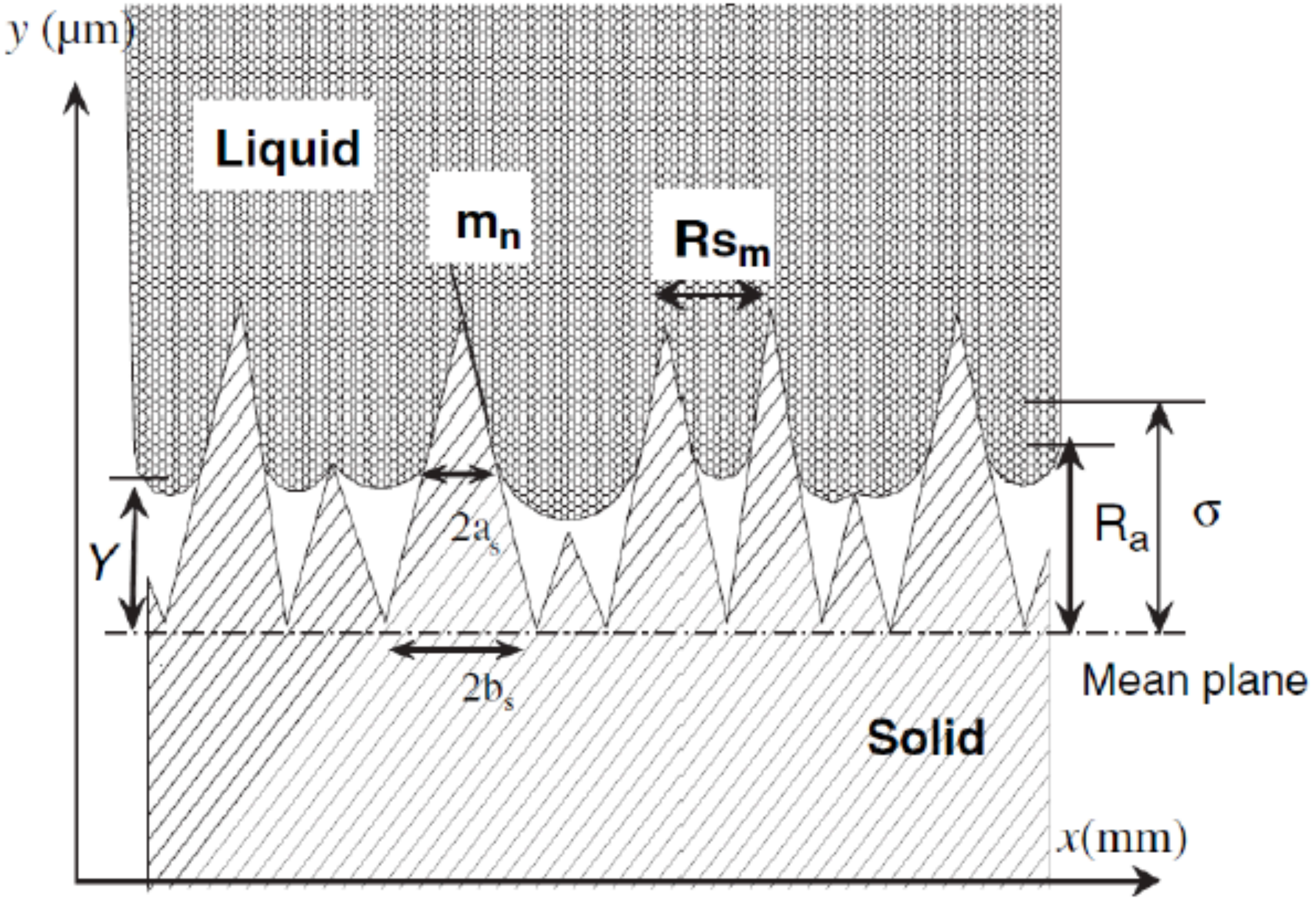
$$q = -hA(\Delta T)$$

Carbon coating high pressure low pressure polished die

Typical die casting	1,000 - 10,000
Natural convection	1 - 10
Flowing air	10 - 50

Die casting contact resistance

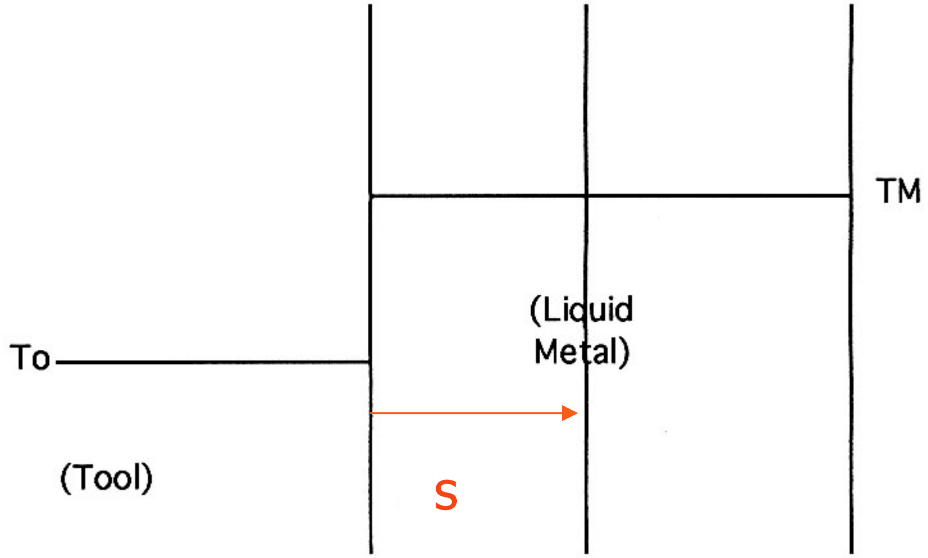
Also see Boothroyd Ch 10, p446-447



A. Hamasaiid, G. Dour, T. Loulou c, M.S. Dargusch; A predictive model for the evolution of the thermal conductance at the casting–die interfaces in high pressure die casting, International Journal of Thermal Sciences 49 (2010) 365–372

Die Casting Solidification Time

Time to form solid part



$$\dot{q} = -\bar{h}A(T_M - T_o) = \rho_M H_M A \frac{ds}{dt}$$

$$\boxed{t = \frac{\rho_M H_M}{\bar{h}(T_M - T_o)} \frac{V}{A}}$$

Also need to cool casting to below T_M

to eject $\rightarrow T_{eject}$

and will inject at $T_{inject} > T_M$.

Time to cool part to the ejection temperature. (lumped parameter model)

$$mC\frac{dT}{dt} = -Ah\left(T - T_o\right)$$

Let, ♪ $\mathrm{\theta = T - T_o}$

$$\int_{\theta_i}^{\theta_f}\left(\frac{d\theta}{\theta}\right) = -\frac{Ah}{mC_p}\int_{t_i}^{t_f} dt$$

Integration yields...

$$t = \frac{-mC}{Ah}\ln\frac{\Delta\theta_f}{\Delta\theta_i}$$

Note C= heat capacity, h = enthalpy

Time to cool part to the ejection temperature. (lumped parameter model)

For thin sheets of thickness “w”, including phase change

$\Delta\theta_i = T_i + \Delta T_{sp} - T_{mold}$

$\Delta T_{sp} = h/C$

$\Delta\theta_f = T_{eject} - T_{mold}$

$$t = \frac{w\rho C}{2h}\ln\left(\frac{T_{inject+\Delta T_{sp}} - T_{mold}}{T_{eject} - T_{mold}}\right)$$

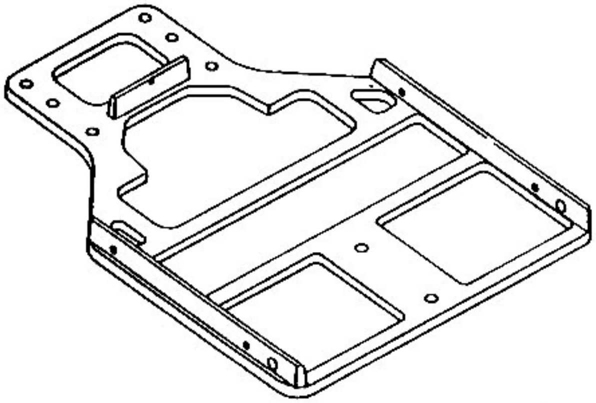
“sp” means superheat
C is heat capacity
h is enthalpy of phase change

Approximations,
$t \approx 0.42$ sec/mm x w_{max} (Zn)
$t \approx 0.47$ sec/mm x w_{max} (Al)
$t \approx 0.63$ sec/mm x w_{max} (Cu)
$t \approx 0.31$ sec/mm x w_{max} (Mg)

Ref Boothroyd, Dewhurst, Knight p 447

Pattern Design Issues (Alum)

- Shrinkage Allowance: 1.3%
- Machining Allowance: 1/16" = 1.6 mm
- Minimum thickness: 3/16" = 5 mm
- Parting Line: even
- Draft Angle: 3 to 5%
- Thickness: even



Pattern Design

Table 12.1

Normal Shrinkage Allowance for Some Metals Cast in Sand Molds

Metal	Percent
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
Yellow brass	1.3 – 1.6
Phosphor bronze	1.0 – 1.6
Aluminum bronze	2.1
High-manganese steel	2.6

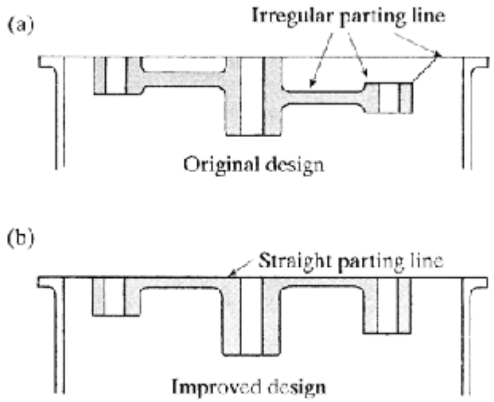
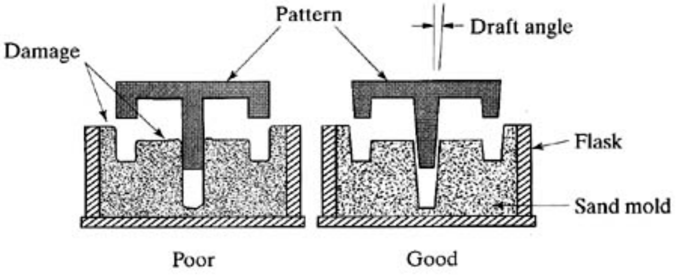
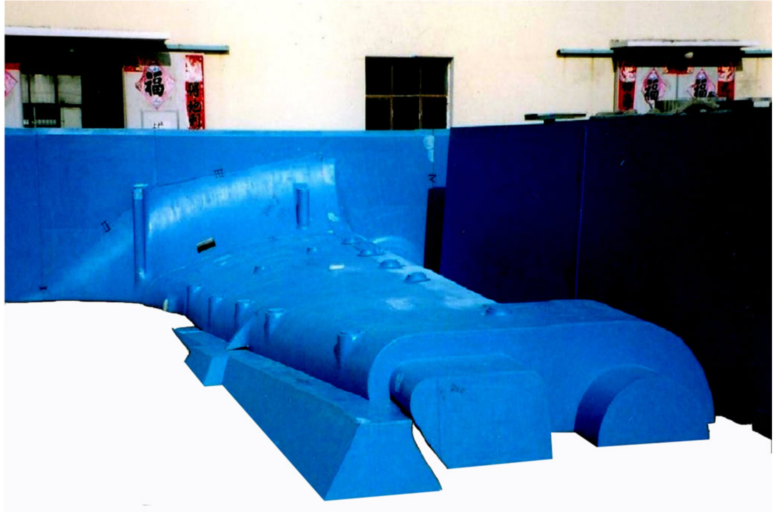


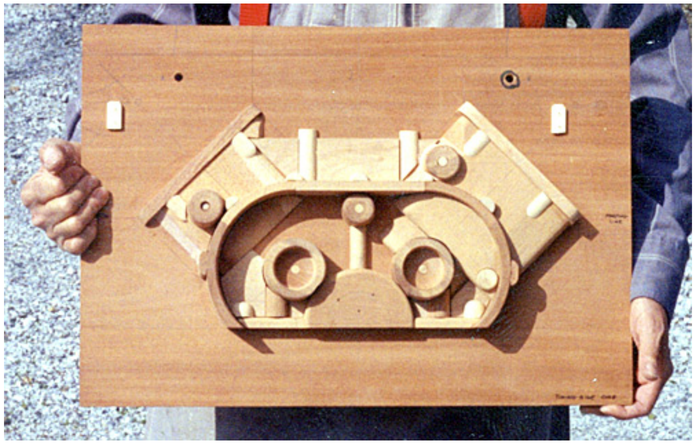
FIGURE 12.5 Redesign of a casting by making the parting line straight to avoid defects. *Source: Steel Casting Handbook*, 5th ed. Steel Founders' Society of America, 1980. Used with permission.

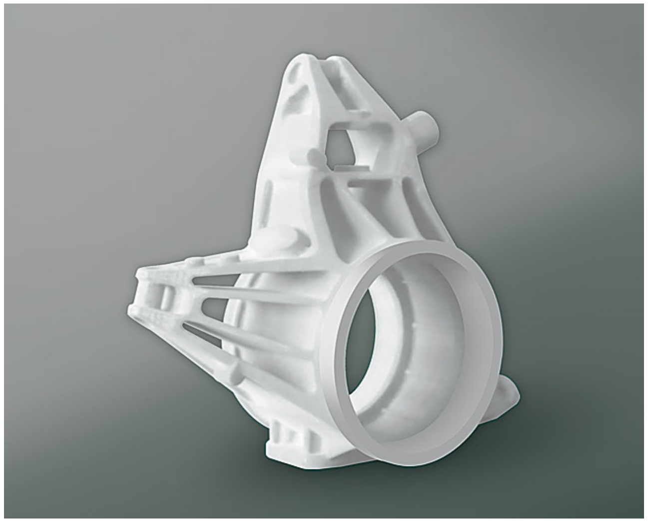
FIGURE 11.7 Taper on patterns for ease of removal from the sand mold.



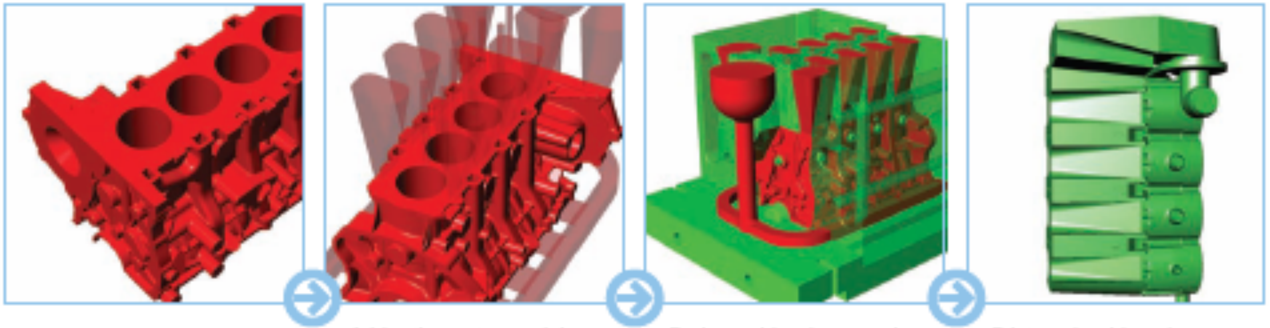
Pattern materials







Digital Sand Casting:
Print molds or parts?

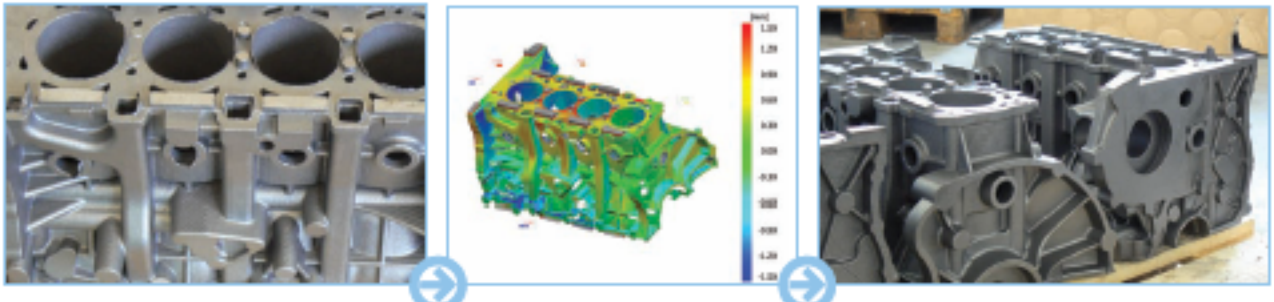


Start from the Computer Model

Add gating system and risers

Design mold and core package, without draft angles and regardless of undercuts

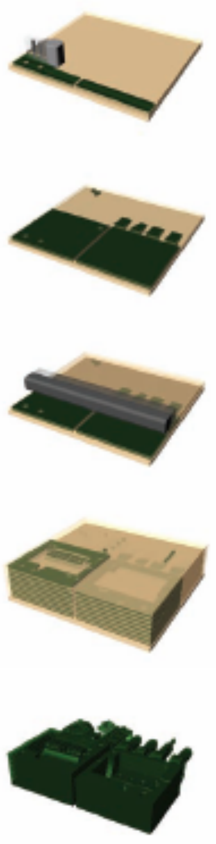
Print sand molds and cores



Casting is poured & ready

Casting is inspected

Parts are ready to be dispatched



1. Print
Selectively dispense binder using inkjet printing technology

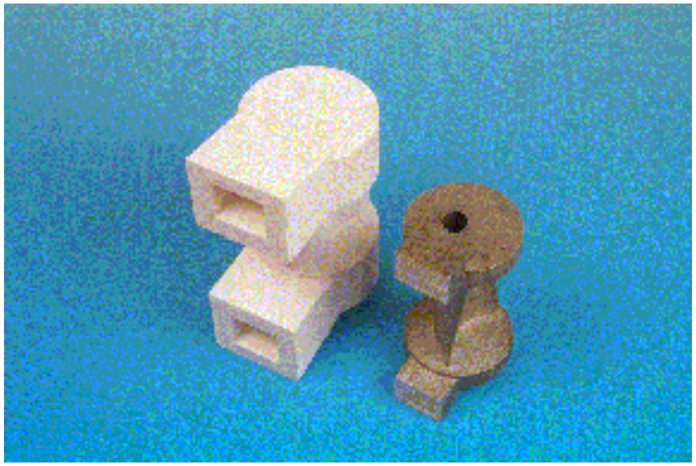
2. New layer
The build platform is lowered by a set increment.

3. Spread
Spreads a new layer of pre-mixed molding sand.

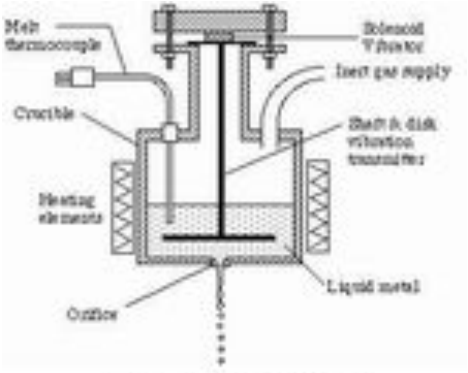
4. Repeat
Repeat Steps 1-3, until the molds or cores are built.

5. Finishing
Unbound sand is removed. Metal parts can be cast.

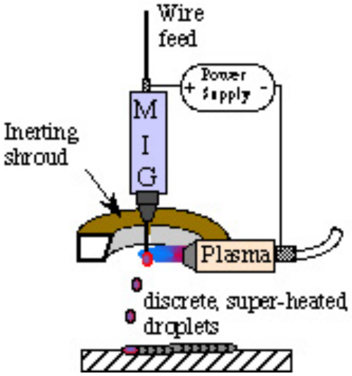
Early Versions of 3-D printing



Printed mold and cast part
Ely Sachs, MIT



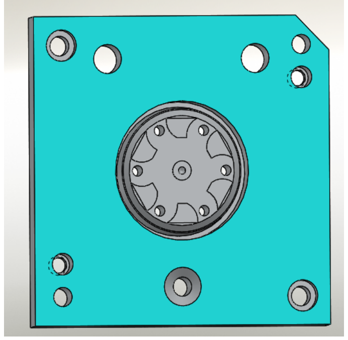
Liquid metal droplets
Jung-Hoon Chun, MIT



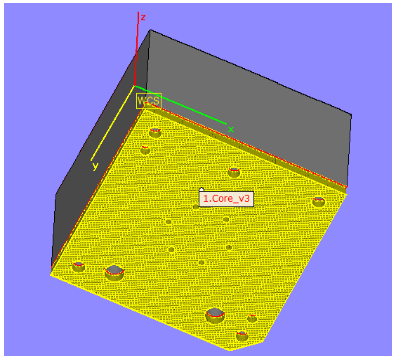
Liquid metal dropets
CMU

Printed steel & aluminum tools

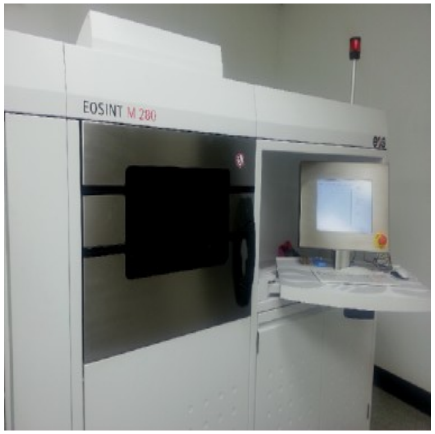
Additive Steps to produce tooling



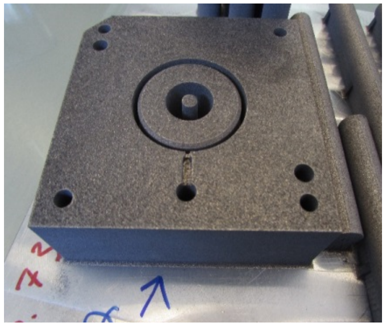
CAD file



Support structure generation

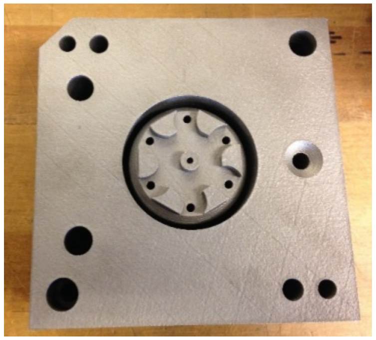


Printing: EOS M280



Printed part on plate, stress relieve

Sawing (or wire EDM) and hand tool removal of support structure



3D printed part

Laser melting of powders

<u>Common laser power:</u>

Polymers ~ 50 W (CO_2 10.6μm)

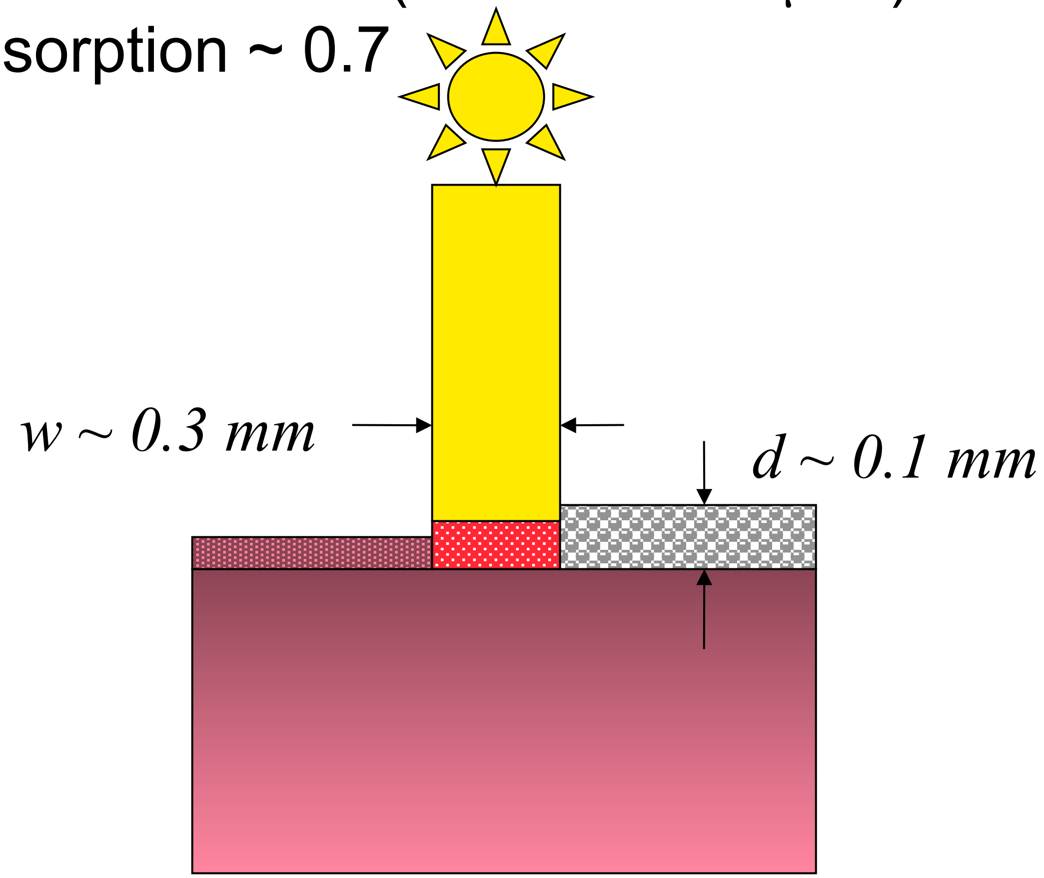
Metals ~ 200 W (Nd:YAG 1.06μm)

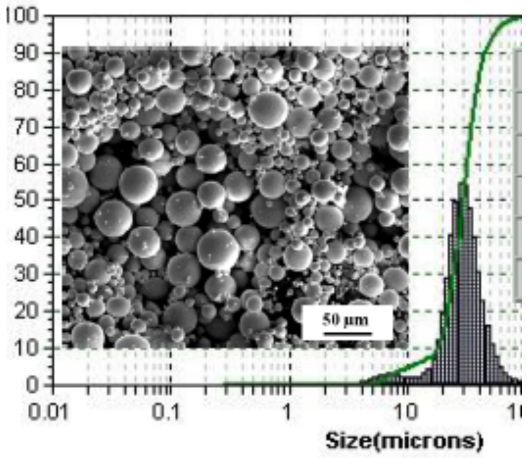
Absorption ~ 0.7

<u>Laser scan speeds</u>

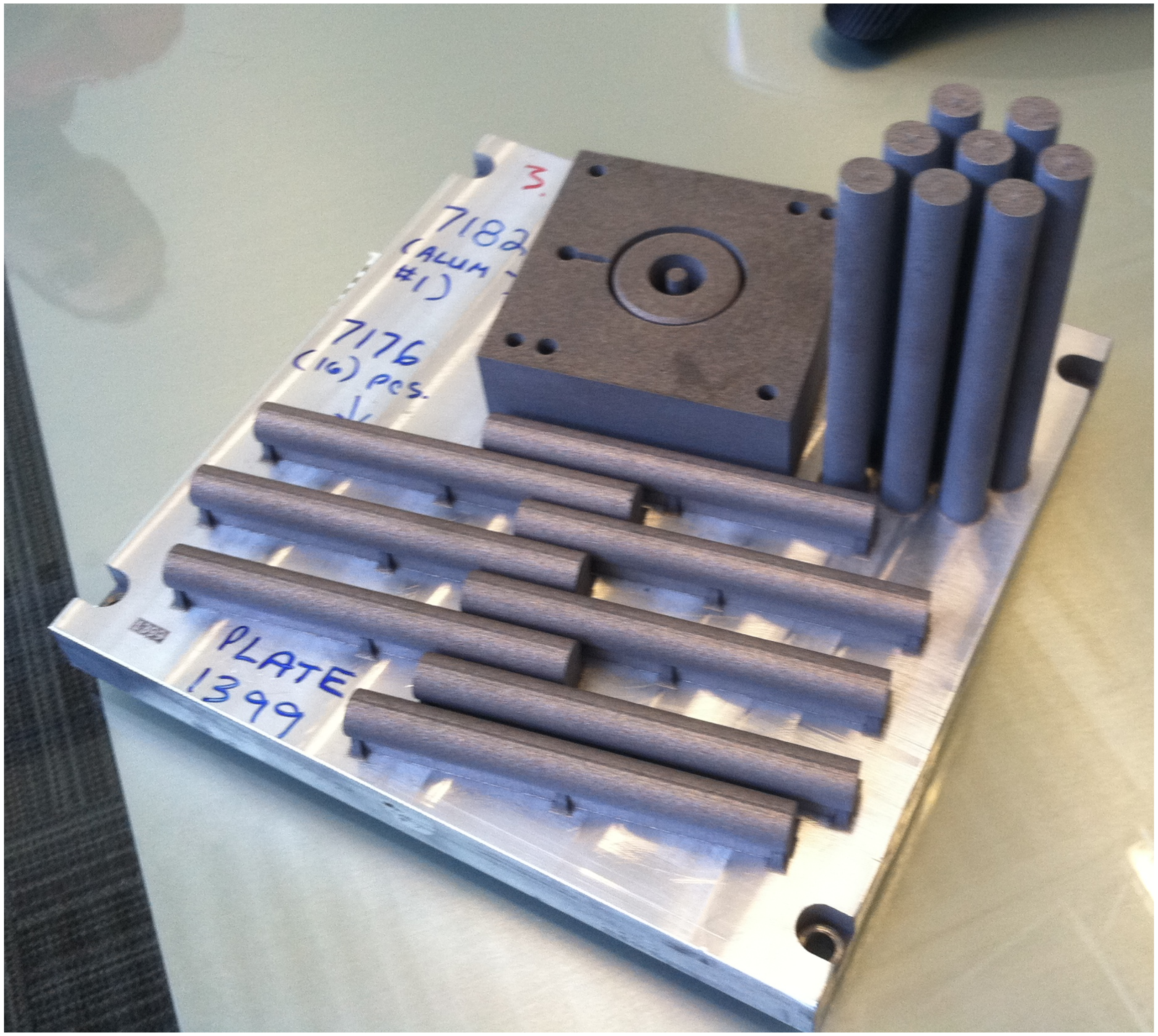
~ .1 to 1 m/s

“max” build rate:
30mm^3/s
= 108 cm^3/hr



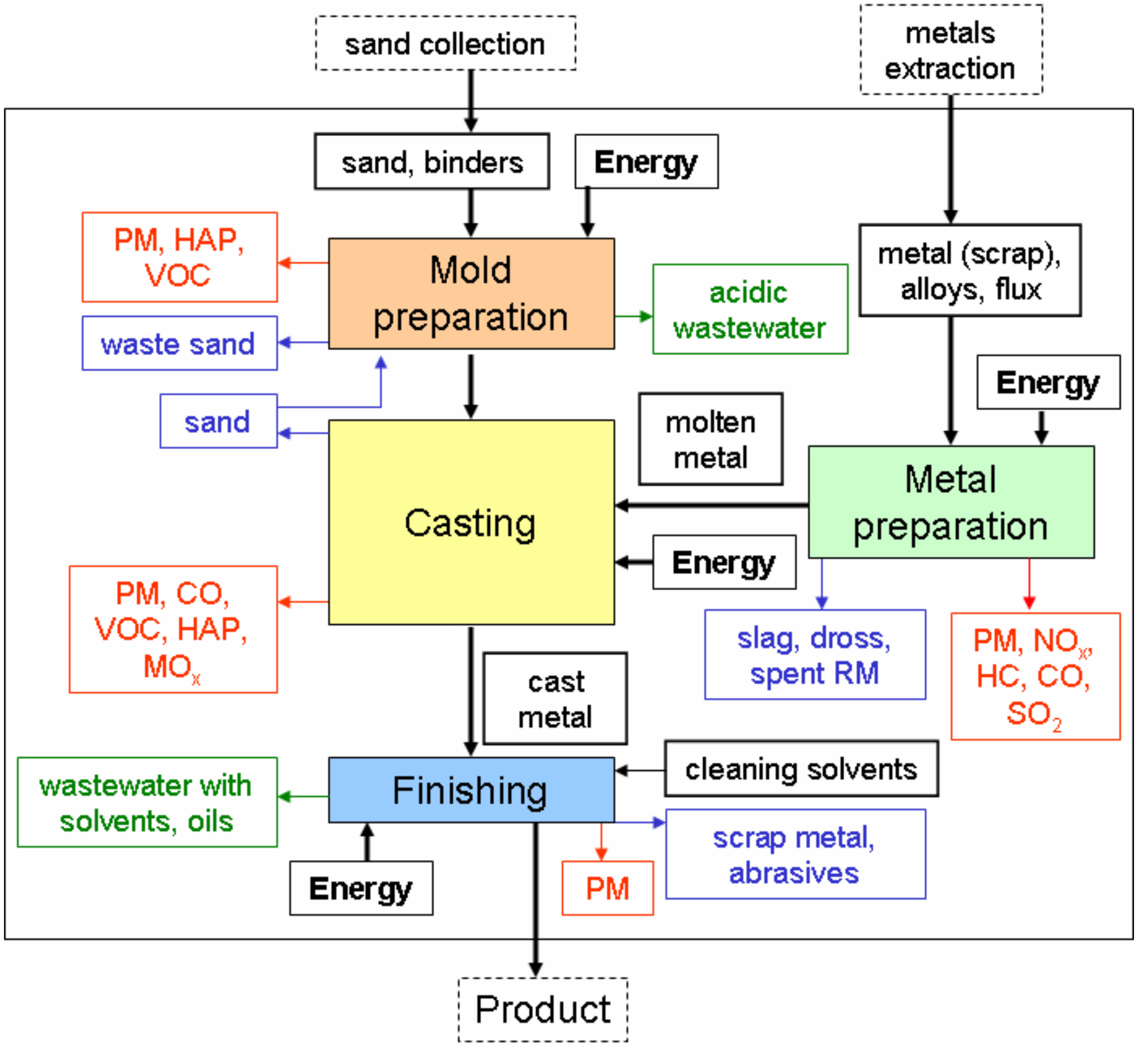


Actual Build



Sand casting; Environmental Issues

- Energy
- Emissions
- Sand
- Waste water



sand collection

metals extraction

sand, binders

Energy

PM, HAP, VOC

Mold preparation

acidic wastewater

metal (scrap), alloys, flux

waste sand

Energy

sand

molten metal

Casting

Metal preparation

Energy

PM, CO, VOC, HAP, MO_x

slag, dross, spent RM

PM, NO_x, HC, CO, SO_2

cast metal

cleaning solvents

wastewater with solvents, oils

Finishing

scrap metal, abrasives

Energy

PM

Product

input

vapor waste

aqueous waste

solid waste

included in analysis

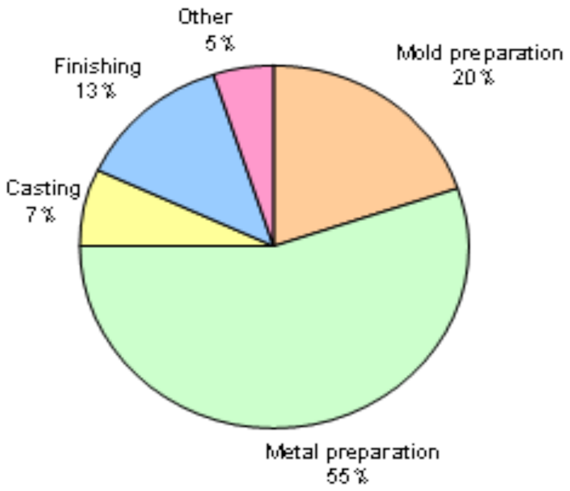
not included in analysis

S. Dalquist

Cast Iron Example (Cupola)

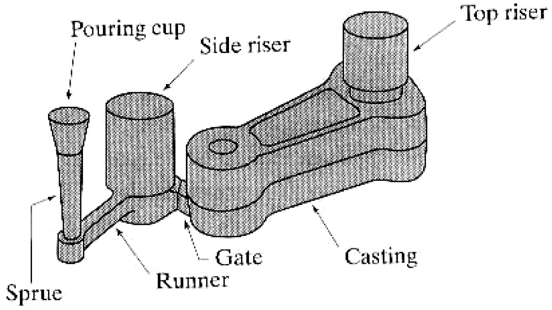
Stage	MJ/kg
Mold preparation	3.0
Metal preparation	6.7
Casting	0.7
Finishing	1.2
Total at foundry	11.6
Electricity losses	0.0
TOTAL	**~12 MJ/kg**

Source: EIA, 2001.



Source: DOE, 1999.

Melting Energy



- pour : part size Ratio ~ 1.1 to 3
- thermal energy

  $\Delta H = mC_p\Delta T + m\Delta H_f$ => 0.95 (aluminum), 1.3 MJ/kg (cast iron)
- melting and holding efficiency,
- *Losses at the utilities for electric furnaces*

•National statistics *(including elect losses)*

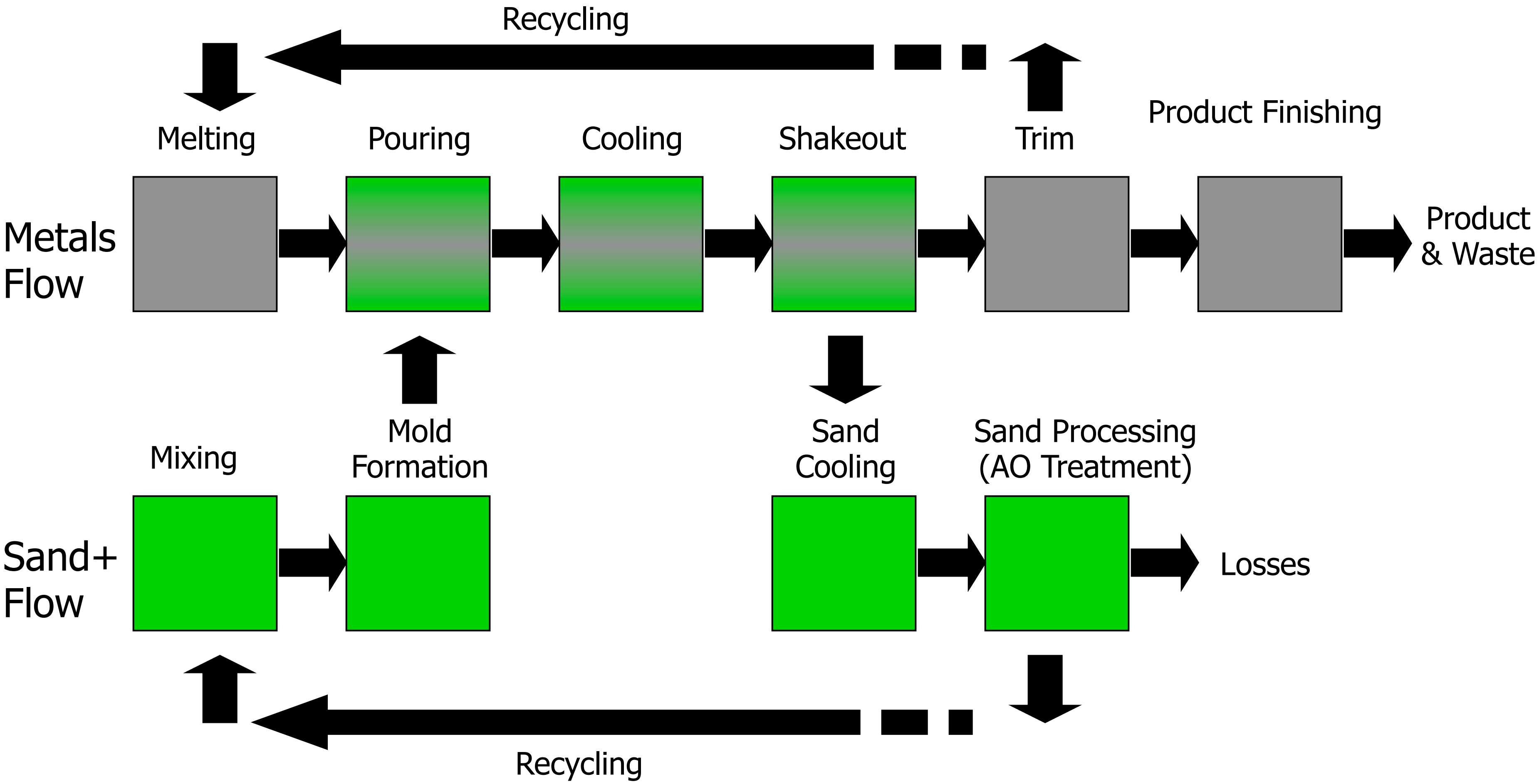
13 – 17 MJ/kg (total)

Improving sand casting

$$\eta = \frac{C_p \Delta T + \Delta h}{15 \frac{MJ}{kg}} \cong \frac{1}{15} \cong 7\%$$

- reduce runners, risers
- recycle metal & sand
- improve furnace efficiency
- use waste heat
- use fuel Vs electricity

Process Material Flow



Recycling

Melting

Pouring

Cooling

Shakeout

Trim

Product Finishing

Metals Flow

Product & Waste

Mixing

Mold Formation

Sand Cooling

Sand Processing (AO Treatment)

Sand+ Flow

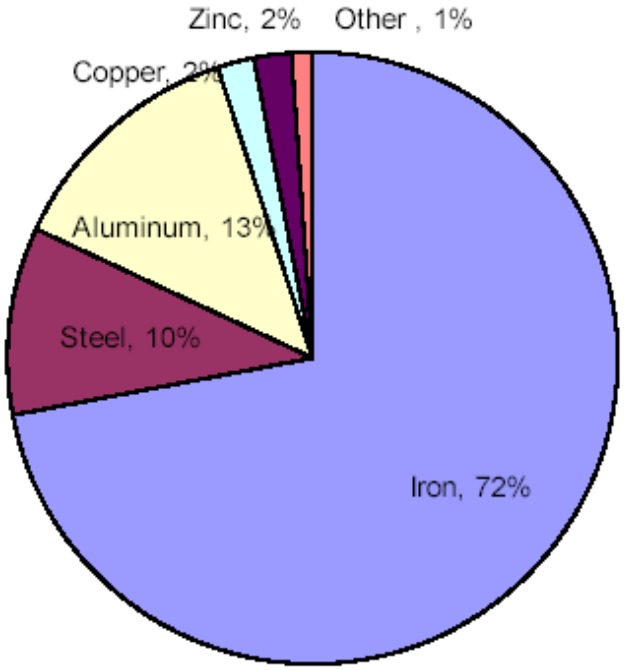
Losses

Recycling

A. Jones

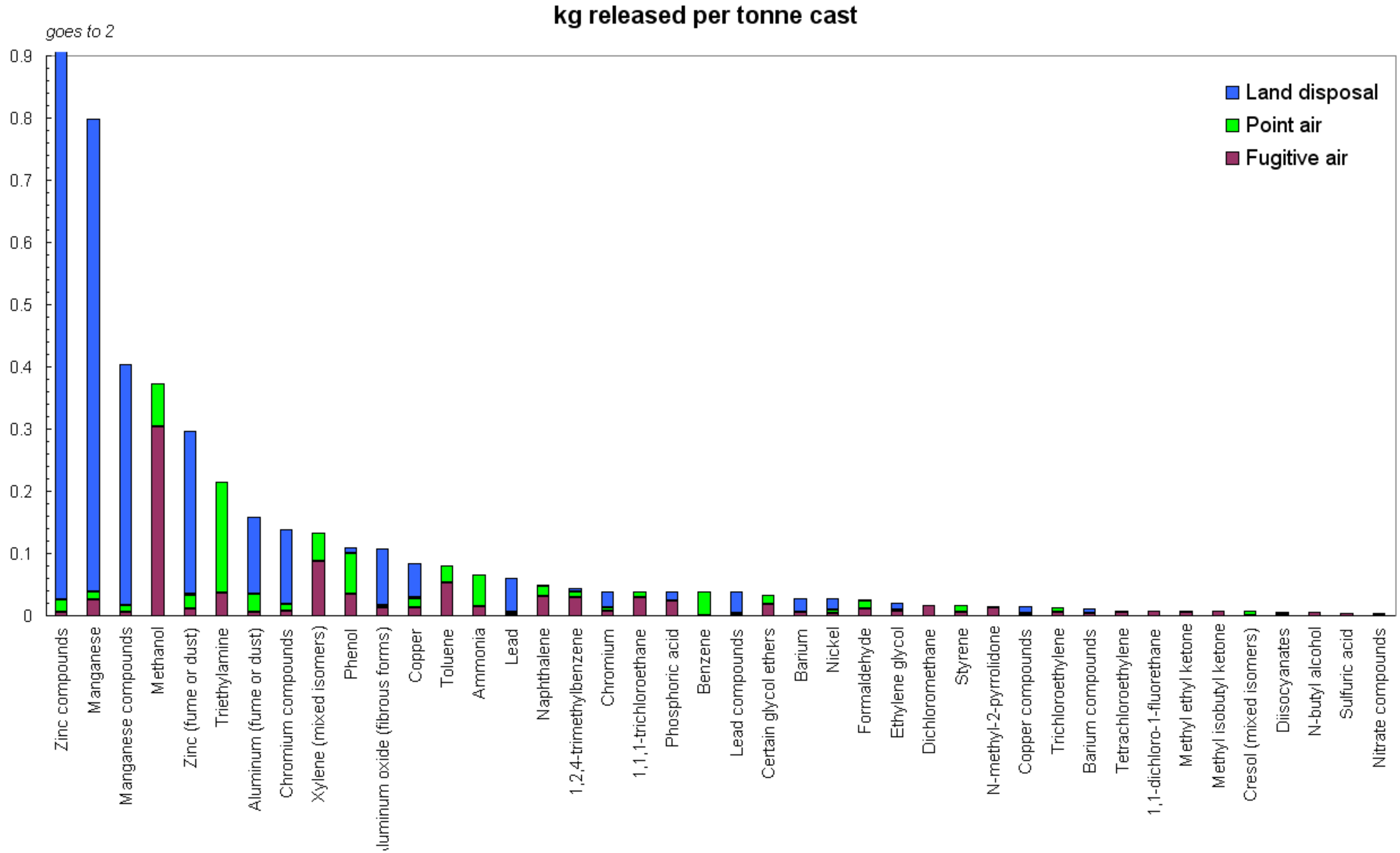
Metals & sand used in Casting

- Iron accounts for 3/4 of US sand cast metals
  - Similar distribution in the UK
  - Share of aluminum expected to increase with lightweighting of automotive parts
- Sand used to castings out– about 5.5:1 by mass
- Sand lost about 0.5:1 in US; 0.25:1 in UK



Source: DOE, 1999.

Aggregate TRI data (toxic releases)



Sandcasting Emissions Factors

- Emissions factors are useful because it is often too time consuming or expensive to monitor emissions from individual sources.
- They are often the only way to estimate emissions if you do not have test data.
- However, they can not account for variations in processing conditions

Iron Melting Furnace Emissions Factors
(kg/Mg of iron produced)

Process	Total Particulate	CO	SO_2	Lead
Cupola				
Uncontrolled	6.9	73	0.6S*	0.05- 0.6
Baghouse	0.3			
Electric Induction				
Uncontrolled	0.5	-	-	0.005 - 0.07
Baghouse	0.1			

*S= % of sulfur in the coke. Assumes 30% conversion of sulfur into SO_2.

Source: EPA AP-42 Series 12.10 Iron Foundries
http://www.epa.gov/ttn/chief/ap42/ch12/bgdocs/b12s10.pdf

Pouring, Cooling Shakeout Organic HAP Emissions Factors for Cored Greensand Molds
(lbs/ton of iron produced)

Core Loading	Emissions Factor
AFS heavily cored	0.643
AFS average core	0.5424
EPA average core	0.285

Source:AFS Organic HAP Emissions Factors for Iron Foundries
www.afsinc.org/pdfs/OrganicHAPemissionfactors.pdf

TRI Emissions Data – 2003

XYZ Foundry (270,000 tons poured)

Chemical	**Total Air Emissions (lbs)**	**Surface Water Discharge (lbs)**	**Total on-site Release (lbs)**	**Total transfers off site for waste Management (lbs)**	**Total waste Managed (lbs)**
COPPER	69	9	78	74,701	**74,778**
DIISOCYANATES	0	0	0	20	**20**
LEAD	127	40	167	39,525	**39,692**
MANGANESE	274	48	322	768,387	**768,709**
MERCURY	14.35	0	14.35	0.25	**14.6**
PHENOL	6,640	5	6,645	835	**7,484**
ZINC (FUME OR DUST)	74	0	74	262,117	**262,191**
TOTALS			**7,300**	**1,145,585**	**1,152,889**

Input Metals for Casting