ME5005/ME4002
DESIGN FOR MANUFACTURE
PRODUCTION ENGINEERING

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Lecture 5: Casting mechanics

Heating for casting

- All metals to be cast will require energy to:
  - Raise the temperature of the raw material to the melting point
  - Change phase from solid to liquid (heat of fusion)
  - Increase molten metal temperature to pouring temperature
    - decrease in viscosity with temperature
    - Allows molten metal to flow easily into extremities
    - Difference between pouring and freezing temperature known as *superheat*
- The *rate* at which this energy is removed will effect the final microstructure of the casting

Energy required for casting

- Total energy E required for casting:

$$E = \rho V[C_S(T_m - T_0) + H_f + C_L(T_P - T_m)]$$

- Approximate value of E only as:
  - C_S and C_L not constant, vary with temperature
  - ρ different for solid and liquid phases, varies with temperature
  - H_f difficult to calculate for alloys with a long freezing range
  - Does not include heat loss to environment
- Gives an indication as to the size/cost of the furnace required

Bernoulli's equation for pouring

$$h_1 + \frac{P_1}{\rho} + \frac{v_1^2}{2g} + F_1 = h_2 + \frac{P_2}{\rho} + \frac{v_2^2}{2g} + F_2$$

- where:
  - h_1 is the *head* (height difference), in m
  - P_1 is the *pressure* on the liquid, in Pa
    - injection pressure or atmospheric pressure
  - ρ is the molten metal *density*, in kg.m^{-2}
  - g is *gravity*, in m.s^{-2}
  - v is the *flow velocity*, in m.s^{-1}
  - F is the head loss due to *friction*, in m

Simplification of Bernoulli's eqn.

- Ignoring friction (not possible in sand moulds)
- Assuming constant pressure (e.g. atmospheric)

$$h_1 + \frac{v_1^2}{2g} = h_2 + \frac{v_2^2}{2g}$$

- Let point *1* be the top of the runner/sprue, and point *2* the base: assume $v_1 = 0$
- Make point 2 the reference plane, hence $h_2 = 0$
- h_1 is then the height of the spru

$$h_1 = \frac{v_2^2}{2g}$$

Mould fill time (MFT)

- Hence:

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

- Assuming an incompressible liquid, the *volumetric flow rate* Q will be constant:

$$Q = v_1A_1 = v_2A_2$$

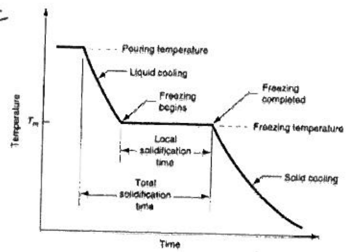
- as *v* varies with *h*, the sprue must be *tapered* to prevent air being aspirated into the liquid
- The mould fill time may then be estimated:

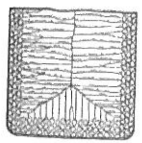
$$MFT = \frac{V}{Q}$$

- Mould fill time should be ________ to reduce occurrence of misruns and cold shuts

Solidification – pure metals

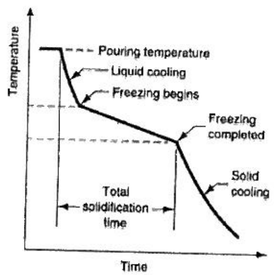
- Pure metals and eutectic alloys solidify (*freeze*) at a constant temperature
  - Latent heat of fusion released into surrounding mould
- Metal in contact with mould solidifies rapidly
- Metal in centre of casting cools more slowly
- Produces a characteristic columnar grain structure in the centre

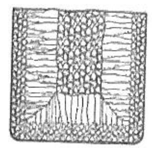




Solidification - alloys

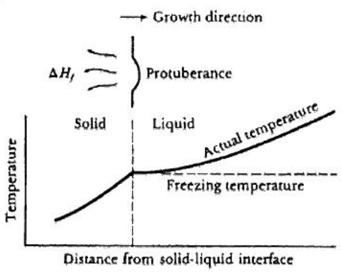
- Most other alloys freeze over a temperature range
- Alloy touching the mould solidifies first
  - Solid rich in one constituent
- Last solid to form has different composition
- *Microsegregation* occurs within individual grains
- *Macrosegregation* occurs across the casting





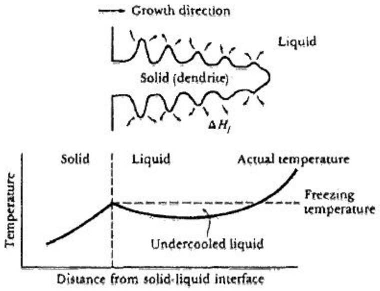
Planar growth

- May occur at slow cooling rates that allow diffusion
- Latent heat of fusion H_f conducts through the solid to the surroundings
- Any protuberance that develops is surrounded by liquid metal above the freezing temperature
- Protuberance stops growing until the planar interface catches up



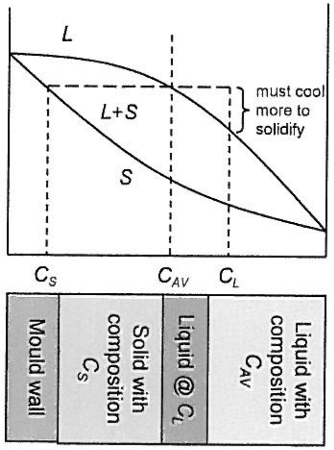
Dendritic growth

- During rapid cooling it is hard for crystals to form
  - poor nucleation
- First solids to form (*embryos*) are small and unstable
  - Critical radius required
  - Re-melting occurs requiring energy from the surrounding liquid
  - produces *UNDERCOOLING* where the liquid is *below* the freezing temperature
- Latent heat of fusion conducts into the *undercooled* liquid
- Non-planar growth results
  - Tree-like *DENDRITES*



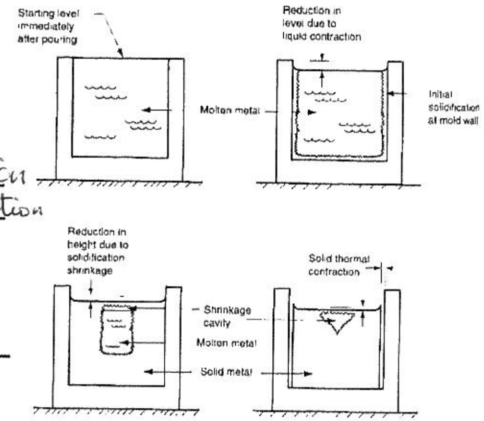
Dendritic segregation

- First solid to form is rich in one constituent
  - Adjacent liquid layer has deficient composition, C_L
  - Liquid bulk has average composition, C_{AV}
- Adjacent liquid layer @ C_L must cool further before solidification can occur
- Dendrites break through this layer and allow liquid in the bulk to solidify
- Liquid @ C_L trapped between dendrite branches
  - Constitutional segregation
  - May lead to porosity



Casting shrinkage

- As the casting solidifies and cools, shrinkage will occur due to:
  - Solidification
  - Thermal contraction
- Additional molten metal is required to compensate for shrinkage
  - 'feeding' system

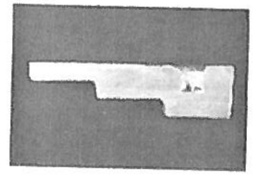


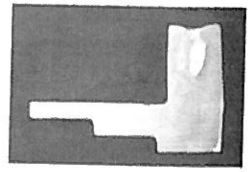
Volumetric contraction

	Solidification shrinkage (%)	Solid thermal contraction (%)	Total (%)
Aluminium (pure)	7.0	5.6	12.6
Aluminium (alloy)	7.0	5.0	12.0
Cast iron	1.8	3.0	4.8
Cast iron, high carbon	0.0	3.0	3.0
Cast steel, low carbon	3.0	7.2	10.2
Copper	4.5	7.5	12.0
Bronze	5.5	6.0	11.5

Riser

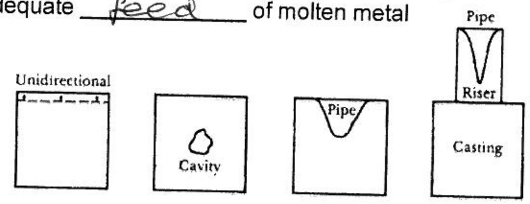
- A *riser* is added to the pattern/mould design
  - Supply of extra material to ensure correct final geometry of component
- May be any shape
  - Simple cylinder
  - Extension of component geometry
- Designed so that the shrinkage cavity (*pipe*) occurs in the Riser
- Must be machined off
  - Post-processing cost
  - Material wastage





Shrinkage types

- Unidirectional shrinkage due to thermal contraction
- Solidification shrinkage produces:
  - Cavity defects (enclosed mould/geometry)
  - Pipe defects (open mould)
- Pipes may be contained in the riser
- Cavities must be eliminated by good design
  - Adequate feed of molten metal



Solidification sequence

- To prevent shrinkage cavities, a *feeding path* must exist from the extremities of the mould back to the riser
  - Order in which component sections solidify must be known
  - Extremities must solidify first
- Riser must solidify last to maintain supply of molten metal to counteract shrinkage
- Use Chvorinov's rule to calculate solidification times:

Chvorinov's rule

$$t_S = B\left(\frac{V}{A}\right)^n \qquad \text{(usually } n = 2\text{)}$$

- t_S is the solidification time for the casting
- Mould constant B dictates the *rate* of heat transfer through the mould and depends on:
  - Mould material (sand, metal dies)
  - Thermal properties of cast metal (solidified layers)
  - Pouring temperature
  - Ambient conditions
- B must be determined experimentally

Chvorinov's modulus

- Chvorinov's rule may be applied to individual sections of a component
  - Assume mould constant is the same throughout the geometry
- Sections must be designed so that the extremities have the shortest solidification times, the riser the longest
- Non-cooling areas of the surface area of each primitive must be accounted for
- Chvorinov's *modulus* is calculated for each primitive:

$$M = \frac{V}{A_S - A_{NC}}$$

- Section with the smallest modulus will solidify first

Casting calculations

- Estimate minimum volume of riser
  - Use 12% of total volume if metal not specified
- Divide component into simple primitives
  - Roughly equal size and shape if possible
- Calculate modulus for each primitive
- Determine solidification sequence and feed path
  - Lowest modulus solidifies first
- For one primitive A to feed another primitive B:

$$M_A \geq 1.2M_B$$

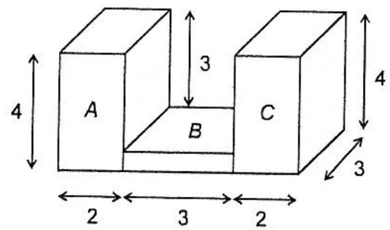
- Determine preliminary feeder location(s)
  - Use minimum number, only one if possible

Redesign component

- Component must be redesigned to suit the casting process, provided that the end use is not compromised
  - Functionality
  - Strength
  - Restrictive geometry
- Eliminate any unnecessary geometry that the process is incapable of producing
  - e.g.: very thin sections
- Reshape to produce desired moduli and feed path
  - Reduce sections where possible rather than enlarge (uses less material)

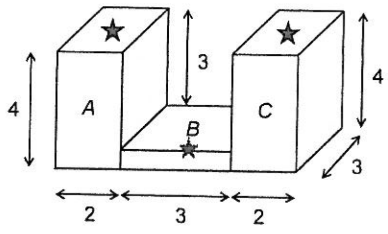
Worked example

- Primitives A and C:
  $V =$
  $A_S =$
  $A_{NC} =$
  $M = 0.490$
- Primitive B:
  $V =$
  $A_S =$
  $A_{NC} =$
  $M = 0.375$
- B solidifies first
- A or C can feed B



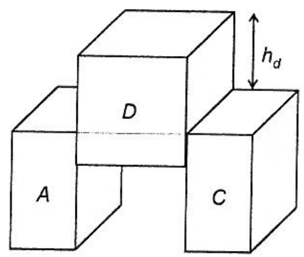
Feed path calculations

- Feeder volume:
  $V_T =$
  $V_F = V_T \times 0.12 = 6.84$
- A single feeder on A or C has no feed path through B
- Can a single feeder on underside of B be used?
- Recalculate modulus of B with new non-cooling area
  $M_B = 0.6 \geq 1.2 M_{A,C}$



Feeder check

- Minimum feeder height h_d:
  $V_D = V_B + V_F =$
  $$h_d = \frac{V_D}{A} - h_b = 0.76$$
- Primitive B plus riser becomes new primitive D
- Must calculate M_D:
  $V = 15.84$
  $A_S =$
  $A_{NC} =$
  $M_D = 0.478$
- Must increase M_D to ≥ 0.588 for primitive D to feed primitives A and C
- Increase height of D
  - New height h_d?



Effect of material type

- Pure metal/eutectic alloy
  - Solidification contours may be predicted by considering direction of heat flow
  - Modulus technique relatively accurate
- Long freezing-range (≥100°C) alloy
  - Dendrites grow into each other and may block the feeding path, leading to porosity in sections less than 5cm thick
  - Sections should be tapered
  - modulus should increase by 3.5% per cm
- Short freezing-range (≤50°C) alloy
  - Modulus should increase by 1.0% per cm