ME 206 Manufacturing Processes I (S1)

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Note : In this course, notes for some parts of syllabus before midsem are missing

1 Introduction

- The five M's of the manufacturing define the profitability of the manufacturing process
  - Men (women)
  - Machine
  - Materials
  - Money
  - Management
- Manufacturing processes can be classified into:
  - Shaping processes
  - alter the shape
    * Solidification process
    * Metal Removal process
    * Deformation process
    * Assembly process
  - Property enhancing processes
  - change the properties of the material
    Ex: annealing, hardening
  - Surface enhancing processes
  - clean the surfaces or coat them
    Ex: Surface oxidation
- Selection of manufacturing processes depends on various factors
  - Cost
  - Available infrastructure
  - Operating temperature
  - Required properties
  - Dimensions of required product

2 Casting Process

Pros:

- Complex forms, low cost
- Certain shapes cannot be machined
- One piece parts vs. multiple piece parts
- Design changes are easily incorporated
- High volume, low skilled labor
- Large, heavy parts can be made easily

Cons:

- Problems with internal porosity
- Dimensional variations due to shrinkage
- Trapped impurities, solids and gasses
- High-tolerance, smooth surfaces not possible
- More costly than stamping or extruding in some cases

2.1 Pattern

- It is the replica (usually a bit bigger) of the req product
- It should be cost efficient, easily machinable into common shapes.
  Possible choices are:
  - Wood : more than 90% of the production happens with wood, absorbs moisture, relatively lower life
  - Metal: longer life, used in large quantity production, Al, cast iron and bronze are most used
  - Plastic : good corrosion resistance, smooth surfaces, do not absorb moisture, dimensionally stable, low weight
- Pattern types
  - Single piece pattern: Name says it all
  - Split pattern
  - Cope
  - split pattern: Same as split pattern except that parts are moulded seperately
  - Gated pattern: Tree like structure with each branch holding the required shape

2.2 Allowances

- Shrinkage Allowance
  When the metal changes from liquid to solid state and cools downs in solid state, its volume reduces. So we make the pattern size more than the size required. This is called shrinkage allowance.
- Draft/ Taper Allowance
  To avoid damage to the sand mould and casted metal on the internal walls while removing the metal after it cools, we need to provide extra material on the walls of the pattern. We typically use a tapering angle(angle at which pattern is bent outwards) of $1\,\mathrm{deg}$ to $3\,\mathrm{deg}$.
- Machining/Finishing allowance
  It is the extra material allowed to cut to smooth finish the product. The amount of machining depends on method of moulding method of molding and casting used, size and shape of casting, metal used in casting, required accuracy and finish
- Distortion / Camber allowance
  Due to typical shape of some patterns (non symmetric) (T, U, V, W), after cooling down the shape will change due to uneven shrinkage, so we need to allow distortion allowance i.e, we need to bend the pattern in opp dir to the expected distortion to get correct shape. This varies between 2 to 20 mm.

2.3 Molds

- Expendable Molds: A new mold has to be produced for every cycle. Types: green sand, dry sand, shell, investment, plaster
- Permanent molds: Multiple usages, used in: die casting, centrifugal, pressure die, injection molding
- Required properties of moulding sand:
  - Refractoriness: Ability to withstand higher temperatures
  - Permeability: For the air to escape
  - Cohesiveness: Adhesive forces in sand
  - Flowability: It should flow uniformly to all the portions

2.4 Gates

Gate is the hole through which the molten metal flows into the mould cavity. Mainly 3 types of gates are used:

- Top gating: The gate is present at the topmost portion of the cavity. In this case, the metal poured through the gate hit the mould cavity floor with some force. This can cause the sand to erode and mix up with the molten metal. But this can be avoided by making the passage from runner to gate a bit above the runner floor. This will slow the metal.
- Bottom gating: In this case, gate is present at the lowest part of the mould cavity. After filling some part of the mould cavity, the process slows down as the pressure difference driving the flow of metal is getting reduced.
- Parting line gating: Gate is present at parting line or joining line of cope and drag.
- A top gating design is prefered over bottom gating design and parting gating design because in the case of top gating design, the gravity help the molten metal to flow to intricate corners of the pattern.

2.5 Types of Casting

- Sand casting:
  Advantages - This is cheap, this can be used ferrous and non-ferrous materials. (Non ferrorus metals require high temp)
  Disadvantages - Rough finish
- Investment casting
  - We first create a pattern out of wax(optimisied for this process) and then dip it in slurry (silica). The slurry solidify on the outer surface to req thickness. Then we heat the thing to melt wax and remove the wax completely to create a outer wall for the req shape. The liq metal is poured into the solid slurry to create the req shape. After cooling down, outer shell can be removed
  - This has a smooth wall finish
  - It can be used to create complex shapes because wax can be easily bended
  - Also known as lost wax casting precision casting
  - This is relatively expensive compared to sand casting
- Centrifugal casting
  - Molten metal is poured into a long cylinder and rotated, and it is cooled on the outer surface
  - The outer part cools faster and have smaller grain size
  - The lighter impurities present in the metal get accumulated at the inner surface. This can be removed by machining process in the inner surface
- Shell moulding
  - The req shape in metal in heated and some silica or sand made to stick to the metal and a outer shell is made.
  - Then liquid metal is poured into the mould.
  - Axial symmetry things can be made easily by this.
- Lost Foam/ Evaporation Pattern
  - A pattern is created is using polystryene and sand is used to support it.
  - The metal is directly poured into the polystryene and the polymer evaporates and creating req shape
- Continuous casting
  - Partially solidified (outer surface) metal is sent through the roller and cooling liquid is sprayed
  - This creates uninterupted long strands of metal
- (Pressure) Die casting
  - High cost

- The dies are two shapes which lock into each creating a cavity in between.
- Before locking they are sprayed with some liq to prevent sticking of molten metal to die
- Metal is poured is cavity and pressure is applied to molten metal. Pressure ensures that metals reaches all the cavities and ensures that metal reaches everywhere before it start solifidies. After removing ejector pins, dice get seperated.
- Cooling channels are present in the die which cool the metal. The whole can be completed as fast as 1min.
- In cold chamber die casting - higher melting point metals (prefered because it can cost higher to maintain metal in liq state)
- In hot cold chamber die casting - lower melting metal (can also be used for higher melting metal)

2.6 Casting Defects

- Misrun : metal solidified before reaching all places
- cold shut : meeting of two metal streams is not complete, i.e, metal flow was not able to reach parts of the mould cavity where two metal flows meets
- cold shot : Due to turbulence during the pouring of the metal, some solid globules form which become entraped in the metal.
- Sand blow : The gas bubble in the cavity which entered the during pouring (or gases released by metal as it cools) stays in the cavity and create bubble shaped cavity.
- Pinholes : The small pours in the metal which are due to the gases which are released during solidification
- Blowholes : Blowholes are similar to pinholes but with larger holes.
- Shrinkage cavity: Depression or internal void created due to shrinkage of metal volume while cooling is called shrinkage cavity
- Hot tearing : when the casting is restrained from contraction by an unyielding mold during the final stages of solidification or early
- Sand wash : Irregularity in the surface of the casting that results from erosion of the sand mold during pouring

2.7 Trends

- Change in casting metal
  - Steel to ductile iron - lower material and conversion cost
  - Al to Al-Mg-Ti alloys - increase in stength to weight ratio
  - In alloy casting, we need to ensure that the composition remains the same throughout.
- Change in geometry
  - Wall thickness is reducing. This is because in casting of thick pieces, distortion happens and we want straight parts. In case, we have multiple thickness, then we can use chill to start solidification earlier at thicker points
  - Weight reduction and increasing shape complexity

3 Metal flow in typical casting

- Metal flow is turbulent. Turbulence causes mixing with air, sand erosion
- When metal flows against the mold wall erosion, vortex formation (air pocket/slag), splashing against the mold walls, air aspiration(due to reaction with mold material) and metal solidification.
- We can determine the reynold's numbers of molten metal.
- Velocity of the metal gets reduced due to loss by sudden change in cross section, etc.

$$v_{actual} = c_d\sqrt{2gh}$$

- Typical value of c_d is 0.6-0.8
- Friction can be ignored for considering loss in velocity of metal, losses due to change in cross section dominate the losses
- Sprue shape has to be shaped as a fructum pointing downwards because as the velocity of the metal increases (due to gravity), the area of cross section gets reduced ($A_1v_1 = A_2v_2$). If the shape is cylindrical or fructum pointing upwards, the flow seperates from the mould walls and form a air cavity which can lead to defects.
- For multiple top gates, L gate (gate at the end of the sprue) has higher c_d compared to T gate. L gate has the highest flow rate (even if it is the farthest) due to inertia.
- To reduce defects in casting process due to erosion of sand mould, we need to ensure that Stress due to impact > Sand mould strength
- Velocity of the metal should not be very high, because high vel makes erosion and causes defects in metal product
- Desired $Re < 8000$

$$Re = \frac{\rho v D}{\mu}$$

- Surface turbulence (Jetting or fountaining effect) - Weber number
(γ is the surface tension of the metal)

$$W_e = \frac{\rho v^2 d}{\gamma}$$

$W_e < 1$: No surface turbulence
$W_e < 10$: Mild
$W_e < 100$: High turbulence

- Bond number (Related to buoyancy)

$$B = \frac{\rho d^2 g}{\gamma}$$

$B < 1$: Surface tension dominate
$B > 1$: buoyancy force overcomes surface tension and leads to surface instability

3.1 Fluidity

- **Fluidity** in case of metal casting refers to the distance the metal can travel before solidifying. This is different from the physics defination(inverse of viscosity)
- Fluidity can be increased by increasing pressure and/or pouring temperature.
- No of gates has to be increased if the fluidity is low
- Pure metals have higher fluidity than alloys
- Spiral test / honeycomb test can be carried out to find the fluidity. This can also be simulated using finite element analysis software like Ansys etc.
- This also can be roughly estimated by doing some calculations:
Consider a metal at its melting point T_m poured into a channel of radius a with average flow velocity v. Let the metal solidify at a distance L_f in time t. The heat released by metal (latent heat) per unit time is equal to the heat conducted by the mold-metal interface. Let h be the heat transfer coefficient of mold-metal interface. Then

$$\rho_m \pi a^2 V \Delta H = (2\pi a L_f) h (T_m - T_0)$$

$$L_f = \frac{\rho_m v \Delta H a}{2h(T_m - T_0)}$$

- The above expression is valid only for pure metals since the melting point of alloys is not a single point but a range of temperatures
- Fluidity of alloys when solid grains are present can be expressed as

$$L_f = f_s^{cr} V t_s$$

where f_s^{cr} is the critical fraction of solid at which fluid stops

3.2 Aspiration effects in mold filling

- For a mold made up of permeable material (eg sand), the pressure of the metal stream should not be less than atmospheric pressure. Because if this happens gases from the baking of organic compounds in mold will enter the molten metal stream, producing porous casting. This is known as **aspiration effect**.

- Consider a sprue (part between pouring basin and gate) of uniform diameter of height h which lead to a mould cavity open to atmosphere (completely or partially through runner). Let the pressure at the start of the sprue be P and velocity v_1. The pressure at the end of the sprue is P_{atm} (since it is open to atmosphere) and let the velocity be v_2.
  Since the sprue diameter is uniform from continuity equation, we have $v_1 = v_2$.
  By applying Bernouli principle,
  $$P + \rho g h = P_{atm}$$
  $$P = P_{atm} - \rho g h$$
  Here, the pressure is less than the atmospheric pressure which causes aspiration.

4 Joining, Assembly and Welding

4.1 Joining

- Welding, brazing and soldering and adhesive are permanent joints

- Welding is with metal of low temp and brazing is with metal of high temp

4.2 Welding

- Two or more parts are coalesced at their contacting surfaces using heat or pressure.

- We can (depends on metals we use) use another metal to facilate joining of two parts. The external metal should have high solubility with the parts being joined.

- **Pros**:
  - Welding is usually the most economical way to join parts
  - Can be done outside factory environment

- **Cons**:
  - This is usually done manually, so is costly
  - Cannot be easily disassembled

- Welding can be performed in various environment - vaccuum (electron beam welding), normal atmosphere, underwater.

- Fusion welding: We melt the base metals and joined to create a homogenous joint. We can use a filler metal here to bond the two parts. In this, we can provide inert gas environment known as shieding gas.

- Solid state welding: No molten states. One of them is friction stir welding. No molten state prevents the formation of blowholes and pinholes because they do not absorb large amount of gases in molten which is the case in fusion welding. Increasing becoming popular

- Arc welding (Fusion welding): We create an electric arc between electrode and work piece (we bring them close but do not let them touch and apply high voltage between them). This heats up the electrode and the metal melts which acts filler. We need to use shielding gases to prevent absorbtion of gases by metal.

- Friction stir welding: Currently used for aluminium (this can easily get oxidised in fusion welding). In this process, we insert a pin between the parts to be joined and stir it at high speed and to generate heat moving throught the joint, which will join the parts

- Laser welding : This is type of fusion process in which we use laser to melt the metal.

4.3 Fusion welding

- Shielding: When metal is in molten state, its gas adsorbtion capacity is very high which leads to pinholes and blow holes. To prevent this, a inert gas environment is provided. Usually, when the metal in the electrode is consumed, it releases some inert gases which creates shielding.
- Popular welding in this category
  - GTAW - Gas Tungsten arc welding
  - GMAW - Gas
  - SMAW
  - OAW - oxy acetylene welding
- **Arc welding**:
  - We need to maintain a constant optimal gap to maintain the electrical arc.
  - A human cannot perform this very well, so we use machines to perform this. Machines cna do this very efficiently.
- **Resistancee welding**:
- We put the two metal parts in a circuit with high current. Utilisng joule's heating, we melt the metal. The metals are also put under proessure.
- **Oxy aceltylene welding**: We use the oxyaceltylene flame to melt the parts and join them. IN this welding, a lot of mechnaical pressure is not applied

4.4 Solid state welding

- Diffusion welding: We make the two part surface flat and put them together under pressure. We heat the combination under pressure. At high pressure, the area of contact increases and increasing temperature increases diffusion rate. So after some time, the metals have formed a homogenous bond. Usually this is for two parts of same metal

4.5 Parameters to evaluate welding

- **Power density**: Power supplied per unit surface area.
  - If it is too low, heat will be conducted and required temperature will not be achieved.
  - If it is too high, it will vapourise the metal
  - There are some practical ranges for this.
  - For example, in arc welding, it is focused and weld can occur upto alot of depth but in the gas welding, it is no the case
  - Oxyfuel welding(10 Wmm^{-1}) can produce high temperature but as it is spread over alot of area. upto 3500°,
  - Laser beam welding(9000Wmm^{-1}) / electron beam welding (10000 Wmm-1)have a very high pwoer density
  - Arc weldding - 50Wmm^{-1}
  - It has to be high for thick weld
- **Welding speed**: It is high for electron beam but for gas welding it is low. We need to find a optimal speed.
- **Aspect ratio**
  Aspect ratio $= z/(x, y)$
  For high aspect ratio, power density has to high
- Unit energy for melting:
- f_1 Heat received by metal/ HEat given by source (Heat transfer efficiency)
- f_2 Heat received by melt /Heat given to metal (Melting efficiecy)
- Heat used $H_w = f_1 f_2 H$
- Al and Cu present a problem because it has high thermal conductivity. It dissipates a lot of heat that it receives.

- Energy balance equation : Heat delivered $H_w = U_w V$, where U_w is the heat required per unit volume , V is volume
- **Joining efficiency**:
  Joining Effiecieny = vt/P
  v = trasverse speed mm/s
  t = thickness of weld mm
  P = incident power, kW