1. **Metal forming**
   1. **Overview**

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| Metal forming | |
| Size or shape of part is changed by the application of forces exceeding the yield strength and below the ultimate tensile strength of the material. The applied force may be tensile, compressive, bending, torsional, shearing or a combination. | |
| Annealing | |
| General term used to describe heating for:   1. Elimination of directional properties. By heating above recrystallisation temperature, the elongated crystals (also called grains\_ can recrystallise into small equi-axed crystals, eliminating directional properties 2. Elimination of phase change effects, such as to reduce the bad effects of heat affected zone caused by welding 3. Stress relief (if temperature is below phase change or recrystallisation temperature). Known as tempering if controlled. | |
| Heat treatment | |
| Heat treatment for strength.  If dimensional accuracy is important, then done before machining, though it will be difficult. Else as last step to process. | |
| Hot and cold working | |
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| Hot working | Cold working |
| Plastic deformation above recrystallisation temperature.   * As temperature rises, grain growth occurs * At recrystallisation temperature, recrystallisation produces small grains * After that, normal grain growth takes place again. Since this process is gradual, grain size can be controlled by controlling temperature. * If grain final size > original size, a tougher material that is more resistant to crack propagation is created due to grain boundaries resisting crack growth      * Material is stress relieved and isotropic (without directional properties) due to annealing (heating above recrystallisation). * Theoretically the upper limit of temperature is the melting point, but we try to keep the temperature low to minimise oxidation.   + Most metals react with oxygen at high temperatures to form brittle metal oxides on their surface – known as ‘scales’. It results in a poor surface finish. | Plastic deformation below **recrystallisation temperature**.   * Material is work (ie. strain) hardened directionally parallel to elongation of grains. * Work hardening reduces recrystallisation temperature. |
| Advantages & Disadvantages | Advantages & Disadvantages |
| Less danger of metal cracking, especially for materials that are brittle at low temperature   * like Zn, Mo, Mg, W (they have to be hot worked) * As a result, can work larger sections and make extreme shapes without tears. | Increased strength in the direction of cold working |
| Increases strength and ductility if:   * Material has existing defects (e.g. blowholes – casting, porosity – metallurgy) * Material becomes more homogenous due to:   + better diffusion of alloy constituents   + breaking up + distribution of particles of hard constituents   + breaking up and refinement of brittle cast structures that arises from highly directional orientation (often large columnar crystals near surface boundaries) | Increased surface hardness and wear resistance |
| Less power needed than cold working, can use smaller machine | Good dimensional tolerances and surface finish (finishing operations not needed) |
| Faster than cold working | No heating needed |
| Isotropic material | Small parts can be shaped quickly |
| Grain refinement is possible to modify mechanical properties:   * Increasing strength and ductility: Heating to recrystallisation temperature to reduce grain size and induce grain growth from there. Arrest growth by cooling before grains get too large. * Increasing toughness: letting grains grow larger than original, increasing toughness and grains resist crack propagation. |
| Cheaper as no annealing needed to relief stress from work hardening |
| Some metals cannot be hot-worked as they get brittle when hot (hot shortness)   * Steels containing sulphur are brittle when hot due to iron sulphide deposits in steel grain boundaries, need to add manganese to form manganese sulphide | Some metals are too brittle to be cold-worked conventionally (unless done hydrostatically) |
| Poor surface finish (needs additional finishing) due to oxide scales   * Mild steel requires pickling with acid and acetone to remove scales to get shiny surface finish | Work hardening makes subsequent operations difficult |
| Poor dimensional control due to:   * Metal contraction on cooling * Oxide scales on surface | Large parts and high-strength need a lot of energy to cold work; slow and sometimes impossible |
| Expensive and difficult to maintain high temperatures | Reduced corrosion resistance, increased electrical resistance, changed magnetic properties |
| Accurate temperature control difficult because of uneven heating   * Worsened by mechanical deformation heating up workpiece, which may cause local melting | Needs subsequent annealing to relieve stress caused by work hardening |
| Difficulty in lubricating at very high temperatures |
| Decarburisation (loss of carbon to environment) or carbon pick up (absorption of carbon) could occur |
| Expensive dies made of tungsten or molybdenum hot working tool steels, tungsten, ceramics required |

* 1. **Metals**

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| Steels and their compositions |
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| Application of plain carbon steels and cast iron |
| * Cast iron has good dampening properties with minimise vibration because of the high carbon content – used for machine tool bases, engine frames |
| Metals |
| 1. Brass: Cu + Zn. Corrosion resistant, durable and pretty (golden and shiny). But expensive. 2. Steel: corrosion resistant and durable. Expensive. 3. Mild steel: strong, very cheap. But very prone to corrosion. Need to pickle to remove oxidation layer and electroplate with Cr to prevent corrosion. Inert gas shield not needed for welding. 4. Medium steel: strong, but very corrosion prone. 5. Aluminium: Durable, strong, cheap. Not shiny due to oxide layer. 6. Cast iron: corrosion resistant in water due to high carbon content |

* 1. **Rolling**

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| Rolling procedure | |
| Rotating cylinders of certain shape squeezes metal workpiece between them until desired geometry and thickness is achieved.    Hot rolling from ingots   1. Soak hot ingots in pits to achieve uniform temperature throughout the metal 2. Hot roll into blooms (cross section > 15 cm2), billets (cross section 4-15 cm2) or slabs (6-40mm) thick. Hot rolls are rough or notched to ‘bite’ the workpiece. 3. Decide whether hot or cold rolled products are desired.    1. If hot rolled, then finishing operation follows while metal is hot    2. If cold rolled, then cool metal, clean surface by pickling in acid to remove oxide layer. Proceed to cold roll; cold rolls are smooth to give a smooth finish.   Application   * Reduction in thickness normally 1-10% per pass for accurate sheet thickness. If reduction per pass is too high, material will not be pulled through. For greater reduction, extend the mill. * Whether hot or cold depends on requirements for dimensional accuracy and surface finish; as in hot vs. cold working. * Cannot be economically cold rolled if diameter is smaller than 5mm. | |
| 2-high rolling mill | |
| 2-high rolling mill in series  Can be up to 20 in series and is able to produce long strips (up to thousands of metres), bars or sheets, limited only by factory space.    2-high reversing rolling mill  Saves space and suitable for short parts below 10m. On reversal, rolling gap is narrowed and rolls move faster, repeated until final thickness achieved. Needs a lot of power; heavy forces induced in roll-drive mechanism to overcome inertia of reversal. | |
| n-high rolling mills | |
| 4-, 6- and n-high rolls are used to cold roll wide sheets, thin sheets and severely strained hardened sheets. The back up rolls help reduce excessive deflection of the rolls, achieving a more even thickness. | |
| Planetary rolling mills | |
| Behaves like a roller bearing – small work rolls installed in cages are friction-driven by two driving back up rolls. | |
| Small rolls | |
| Advantages | Disadvantages |
| * Cheaper to replace * Can be made of tungsten carbide (much harder and wear resistant than steel) * Tend to spread workpiece less sideways | Weaker than large rolls. |

* 1. **Extrusion**

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| Extrusion |
| Metal is forced to flow through and take on the shape of an opening, called a ‘die’. An extrusion die is the orifice through which the material is *pushed* out and dictates the shape of the extruded product. Analogous to toothpaste being forced out opening of toothpaste tube.  Can be done (metal pre-heated) or cold.  Applications   * For >10mm, cannot be extruded properly if diameter is less than 10mm * Can achieve minimum wall thickness of about 1mm for steel and aluminium, similar to rolling * **Rolling is preferred to extrusion** because it is generally cheaper * Extrusion could result in workpiece surface defects/weakness when the metal leaves the extrusion chamber (high pressure) to atmosphere (lower pressure). * Generally convenient for low melting point and softer metals, provided they are ductile enough * Not for steel generally |
| Direct (forward) extrusion |
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| Hollow extrusion (to create hollows extrudates) – stationary or moving mandrel |
| Stationary mandrel    Moving mandrel (attached to ram) |
| Indirect extrusion |
| Metal emerges from the die in a direction opposite to applied force. Advantage is that there is no frictional force between billet and cylinder walls, as compared to direct extrusion. |
| Indirect hollow extrusion |
| Moving mandrel (attached to ram)    Stationary mandrel (attached to cylinder) |
| Impact extrusion |
| Extrusion done by a sudden blow of a punch.  Properties:   * Applied to soft metals like lead, tin, aluminium; copper and copper alloys need to be preheated to above 600C (hot impact extrusion). * **Can produce one piece per second.** |
| Hydrostatic extrusion |
| Fluid pressure is used to extrude a billet. Thin fluid film passes through the ide with the extrudate, acting as lubricant. Method reduces Mohr’s circle to a single dot, reducing maximum shear stress to 0, making it impossible to fracture.  Applications   * Extruding brittle metals * For achieving high reduction of cross-sectional area |
| Hot extrusion |
| Usually direct extrusion is used so that the metal is easily supported, handled and freed from equipment. Metal is preheated to just below melting point to lower yield strength.    Lubrication   * Oil, graphite mixture for low temperatures (Mg, Al and Cu alloys) * Molten glass for high temperatures (steel)   Applications   * For long pieces of uniform cross-section. E.g. window grills, curtain rails, pipes and tubes, channel sections, angle bars etc. * Economical way to make small parts in large quantities (extrude great length and cut into smaller pieces); extrusion dies are relatively cheap   Maximum cross section   * For Al (ductile), 60cm diameter circle * For steel (hard), 15cm diameter circle |
| Cold extrusion |
| Extrusion done at room temperature, but metal gets hot when extruded due to deformation. Work hardening causes metal to be extrude after a while, so process must be completed fast. |

* 1. **Tensile Drawing**

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| Tensile drawing |
| There is a limit to minimum diameter for rolling (5mm) and extrusion (10mm). So, workpieces can be reduced to smaller cross-sections by tensile drawing as a secondary process.  Process   1. Hot rolled stock is de-scaled and cleaned by pickling in acid and washing with acetone 2. Leading end of the piece is tapered for insertion through the die and pulled through 3. Drawing pressure against the die must exceed yield strength of material   **Direct tensile drawing**    **Hollow tensile drawing (with mandrel)**    Applications   * Normally for small diameter things * For straight things – can get straighter than extrusion   Notes   * When performing tensile drawing on steel, lubricant such as molybdenum disulphide that can function under tremendous pressure must be used. * Reduction in cross-sectional area per pass usually below 40%; if greater reduction is needed then successive passes are used. After a number of draws, work material becomes too hard and brittle (work hardened) and must be annealed to be drawn further. * **Due to high power usage, generally used only if rolling is not possible or suitable for application e.g. rolling vs. extrusion of steel** |
| Tensile drawing dies |
| Made of hard, strong, wear resistant material e.g. hardened alloy steel, cemented carbide, tungsten carbide, cubic boron nitride, diamond |

* 1. **Forging**

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| Forging |
| * Heated or cold metal is deformed by sudden blows or by using very high pressure to squeeze it between dies (plastic deformation). Done cold for dimensional accuracy (finishing process). * Starting material is a rolled billet, rod or bar.   Applications   * Of all manufacturing processes, forging gives best mechanical properties in a workpiece (due to the pressure). Products are durable, reliable, have very high strength, high toughness, high fatigue strength, high surface hardness, wear resistance and density. * Applications for high performance materials (e.g. spoons) * Normally not for very small products (e.g. Allan key) * **Must be solid piece, cannot be hollow. Pattern is possible.**   Flow lines in forged metals   * Squeezing action forces metal to flow in certain directions, creating a fibrous structure. When metal is forged, strength and ductility increase significantly along these lines of flow. * Inclusions (silicates, sulphides) are also forced into these directions. * Flow lines in forging cannot be removed by annealing since they did not originate from cold working. To remove flow lines, need to melt and recast. |
| Closed and open die forging |
| Closed die: force is applied to entire surface of the part, causing metal to flow into the die cavity of specific shape Usually for specific shaping.  Open die: compressive forces are applied locally on different parts of the metal stock without restricting sideways motion of the workpiece. Allows material to spread, usually for rough work.  In both cases, we start with excess material (~30%) to fully fill the die, from which excess will be pushed out as ‘flash’. This flash has to be trimmed off and can be recycled. Less scrap than machining. |
| Hammer forging |
| Application   * Used for considerable reduction in cross-section   Process  Basically like hand forging, but using a machine to hammer.     * Steam-operated or air-operated hammer strikes workpiece repeatedly. Often an open die is used to allow free manipulation of shape. * Operator manipulates workpiece using tongs or using mechanical/hydraulic manipulators to shape the workpiece. |
| Drop forging |
| * Preheated workpiece is shaped by a blow of a board drop hammer in split dies. * Utilises kinetic energy of falling hammer to strike workpiece. * Several progressive dies may be needed to produce the part of final shape. Unlike hammer forging, steam or air is not used. |
| Drop forging |
| * Preheated workpiece is shaped by a blow of a board drop hammer in split dies. * Utilises kinetic energy of falling hammer to strike workpiece. * Several progressive dies may be needed to produce the part of final shape. Unlike hammer forging, steam or air is not used.     Advantages   * **Comparatively high rate of production** * High density of product |
| Press forging |
| * Pressure is applied slowly to squeeze either cold or pre-heated workpiece into shape (plastically deform metal in a die cavity). * Usually hydraulically operated but can be mechanically operated for small pieces that do not need high pressures. * Capacity of press can be up to 50 000 tonnes, 25-100 strokes/min.   Applications   * **For larger sections that cannot easily be handled by drop or hammer forging** * For finishing operations – most press forged parts are initially preformed on other machines * For secondary operations (e.g. to correct dimensional size and improve surface quality of formed part), due to high dimensional accuracy and surface quality   Advantages of press forging over drop forging   * Good surface finish * Good tolerances and accurate dimensions * Good penetration of pressure * Quieter than drop forging * Structural quality more uniform than drop forging   Disadvantage   * Expensive |
| Upset forging |
| * End or some other parts of a long bar is shaped by compression along its length, often using a closed die. * Used to share heads on bolts, nails, gear blanks with stems, etc.   Process   1. Bar stock is firmly gripped in die and a forming tool upsets the preheated metal by exerting an axial pressure 2. Degree of upsetting of stock at a portion is controlled by the shape of the gripping die |
| Roll forging |
| * Similar to hot rolling, used to reduce cross-section of short lengths of bar stock to make long bars. Difference is that stock does not completely pass through the rolls to the other side, and rolls are elliptical in cross section to give a ‘squeezing’ effect. Strengthening effect resembles rolling, while rollers resemble rolling – hybrid process. * Cross-section is reduced while stock length increased. |

* 1. **Sheet metal forming**

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| Sheet metal working |
| * Usually done cold unless the metal sheet is too thick, because hard to heat large piece of metal.   Application dimensions for sheet metal drawing, blanking, piercing and shearing   * Minimum 0.1mm, maximum 2-3mm. But varies with how hard and how ductile metal is. * Often for applications with very low thickness (e.g. beverage cans) with good tolerances. E.g. compare drawing with impact extrusion, which does not give as good tolerances (e.g. fire extinguishers) |
| Shearing of sheet metal |
| Before sheet metal can be formed into useful products, it first needs to be trimmed from the raw material (metal sheets). Shearing is one such process – in contrast, metal cutting refers to turning, milling, drilling and other conventional metal removal processes.  Advantages   * **Fast** * **Amenable to large scale production and automation**   Common operations   1. Shearing – to cut a straight line or curve completely across a strip, sheet or bar (think of tearing paper) 2. Blanking – shearing a whole piece from sheet metal (to get shaped parts) 3. Piercing – shearing holes in sheet metal (to get ‘empty’ parts) 4. Stamping – piercing and blanking 5. Punching – like drawing, where you punch into a contour from sheet metal. Can form hollow half-parts that may be welded. |
| Theory of shear |
| Punch stresses sheet metal beyond its UTS to fracture it.    Clearance   * The space between the punch and the die on each side. If the clearance is correct, the ruptures will result in a blank with good clean edges. The amount of clearance depends on the material and is related to the thickness of the sheet metal * Too much clearance may result in a cup drawing, too little in jagged edges     Allowance   * When a hole is punched, the resulting hole will be smaller than the punch that produced it due to the part of deformation that was elastic. This difference in diameter is called the allowance. * When a piece is blanked, the resulting part is larger than the die that produced it – this difference is also called allowance. * Usually 50μ |
| Calculations |
| Clearance = x% × thickness  Allowance = y  Piercing – to get hole of desired diameter d  Resulting hole in part will be smaller r than die by allowance.  Punch size = d + allowance  Die size is larger than punch size by clearance. Die size = punch size + 2 × clearance  Blanking – to get inner piece of desired diameter d  Resulting part will be larger than die by allowance. Die size = d - allowance  Die size is larger than punch size by clearance. Punch size = Die size - 2 × clearance  Punch force  \* |
| Sheet metal drawing |
| Starting with a flat blank or sheet of metal to form thin metal products by pressing or dorging the blank into a female die while stretching it to confirm to a shape over a male die or punch.  Shallow vs. deep drawing   * Shallow: forming a cup of depth < 0.5 diameter * Deep drawing: cup of depth > 0.5 diameter. More difficult as:   + Wall thinning is more pronounced   + Requires several successive draws with progressive dies   + Annealing may be needed to neutralise work hardening and restore original ductile grain structure   Applications   * Common materials: mild steel, stainless steel, alloys of Al, Cu – any material that is similar in ductility to these. Sometimes heat treatment is used to make a material more plastic. * Thin-walled, seamless cup-shapes * Good uniformity and close tolerances   Process    Main problems:   * Wrinkles * Corner and edge tears |
| Ironing |
| An operation that thins down walls of drawn cups. Often as a secondary operation. |
| Cans |
| 3 piece cans     * Hoop stress at the longitudinal seam = PR/t = 2σaxial   2 piece cans   1. Deep draw 2. Iron the walls 3. Trim the rim 4. Fill can 5. Assemble top disc by seaming (folding around the edges). Rubber sealant to ensure air-tight |
| Cup drawing |
| Calculations   * Draw ratio: . Notice that shell diameter is equal to punch diameter. * Percentage reduction = * Diameter d after drawing = (1 - %reduction)D * Need for annealing   %reduction in area during tensile tests predicts the total reduction in diameter to which a metal blank can be subjected (max = ) before it must be annealed. If metal shows 60% reduction, then blank of diameter day can be reduced to cup of diameter dn such that = after n draws. Note that percentage reduction is cumulative (multiplied), not absolute.  Ie. 4 draws of 40%, 25%, 15%, 10% leaves 0.6 × 0.75 × 0.85 × 0.9 = 0.34, a 66% reduction.   * Number of draws needed (without annealing – can anneal and ‘reset’), using table of percentage reduction of diameter      * Blank diameter needed for shell drawing     Punch force needed for nth draw = cross sectional area of cup wall × yield strength = (πdnt) × σy |
| Rubber pad forming |
| Advantages   * Money is saved because the rubber pad plays the role of the die (no need for costly die), shape imparted by punch * Reduces metal spring back after forming |
| Guerin Process |
| Rubber pad forming process in which several cups of different shapes can be drawn simultaneously with different-shaped punches. |
| Marform Process |
| Rubber pad forming, but blank holder is used to prevent wrinkling of the cup rim. |
| Hydroform Process |
| Rubber pad forming, but oil pressure replaces rubber pad, utilising hydrostatic pressure instead. |

1. **Joining processes – Welding**
   1. **Overview**

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| Welding | |
| Joining by melting metal or applying pressure to the pieces to be joined. A perfect weld is one where the joint is indistinguishable. Usually, surface oxide layers and adsorbed gases prevent perfect welding.  The perfect weld  If two pieces of metal with perfectly clean surfaces are squeezed together in a vacuum, a perfect weld should be formed.     * If tensile forces are applied to separate the parts, failure should occur *outside* the weld area, since the weld area has been strengthened by strain hardening. * In practice, impurities at the weld interface cause the weld region to be weaker than the parent metal. | |
| Ways of achieving welding | |
| 1. **Fusion welding:** melt the metal so that the two parts to be joined flow into each other 2. **Pressure welding:** compress parts together either hot or cold to cause plastic deformation. Can be facilitated by heating the metal to make surface oxides flow more easily and metal more plastic      1. **Fusion welding using added filler material**    1. Parent metal and filler rode should be of same composition and all cooled at the same slow rate to achieve a homogenous weld as strong as the parent metal    2. Weld zone cools faster because it is hotter     Heat affected zones in steel   1. Overheated zone, above 1000C, large grains 2. Annealing zone, 900-1000C, refined grain structure 3. Transition zone, 700-900C, variety of microstructures     Flux  Flux in the form of powder, grains or paste can be used to protect the weld joint from the atmosphere during welding.  Roles of flux:   * Prevents contact of molten metal with atmosphere * Provides a slag blanket to decrease the cooling rate and carry of impurities * Stabilises the weld arc * Reduces oxides * Forms plasma for the arc current * Reduces splatter of the weld metal * Electrically insulates the electrode * Adds alloying elements to the weld * Removes impurities from the molten weld deposit | |
| Advantages and disadvantages of welding | |
| Types of welding defects   1. Dimensional defects    1. Warpage – distortion due to thermal stresses    2. Incorrect weld size and profile due to poor welding technique 2. Structural defects    1. Porosity – due to gases released in metal    2. Incomplete fusion of parent metal due to insufficient temperature, poor manipulation of heat source or inadequate removal of oxide films    3. Lack of penetration in weld    4. Cracking in weld due to lack of pre- or post-heating    5. Surface defects (holes, irregularities) due to bad workmanship | |
| Advantages | Disadvantages |
| 1. Quick and convenient way to join metals 2. Light, since no need for fasteners 3. Easy to make cheap prototype 4. Cheaper, since machining is not needed 5. Does not interrupt stress-flow design (only areas near weld suffer change in microstructure) | 1. Dependent on human factors 2. Surface must be clean for a good weld 3. Fixtures needed to hold parts 4. Weld defects common, quality control methods are needed to check    1. Visual    2. Radiographic (X-ray)    3. Supersonic    4. Holographic |
| Weldability of metals | |
| Almost all metals are weldable.   * **Higher carbon steels and cast iron** need special techniques (pre- and post-heating to prevent cracking and formation of martensite). Considered unweldable if the equivalent C content exceeds 0.5%. Usually steel is only welded if carbon content no more than 0.3%. If cannot be welded, then bolting, adhesives, interference fits etc. can be used.      * **Non-ferrous metals** require special welding techniques depending on their properties (e.g. affinity for atmospheric gases, ease of oxidation, thermal conductivity, changes in material properties caused by heat, etc.) * **Stainless steels** have two potential dangers when welded:   + Sensitisation: stainless steels are stainless because the Cr in it forms a protective surface layer of chromium oxide at room temperature. Between 400 and 850C, the chromium forms chromium carbides with the carbon in the steel, leading to chromium depletion and leaving a steel that is no longer stainless. Can be solved by using low-carbon steel, but that reduces strength. Alternatively, can add Ti, Niobium or Tantalum which preferentially form carbides with the carbon   + Formation of *porous* chromium oxide layer: arc welding without inert gas protection leads to formation of porous oxide layer in addition to chromium carbides, which will not protect the steel from corrosion as it is porous and not continuous. | |

* 1. **Gas welding**

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| Gas welding |
| Mechanism: oxygen + acetylene    Applications   * **When electricity is not available** (e.g. new construction sites), equipment is cheap, portable and versatile * For welding thin sheets below 2mm as temperature below 3500C are much lower than in arc welding (6000C) and more easily controlled |

* 1. **Arc and submerged arc welding**

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| Arc welding | |
| * An electric arc is generated between electrode and workpiece. The arc is an electrical discharge through a path of ionised particles (plasma). * The electrode is *also* the filler rod. Temperatures can reach 6000C.      * Se of flux: shielding from atmosphere may be necessary for good welds if the workpiece material forms brittle oxides – use flux in the form of coated rod powder, paste or use neutral or reducing gas enveloping the arc. The flux will form a protective gas shield. * Electrodes made of the filler metal: they melt and the electrode must be advanced to maintain the arc gap.   Applications   * For joining sections of >2mm thickness * For faster welding with more localised heating, greater depth of penetration than gas welding * For welding materials with high heat conductivity (aluminium and copper alloys) | |
| Submerged arc welding | |
| * Weld joint is submerged under a heap of flux grains (welding ‘within’ flux layer) and shielded from the atmosphere. * Automated since joint cannot be seen * Arc length is maintained automatically. * Consumable electrode acts as the filler rode * There are no sparks, splutter or smoke since the weld is submerged * High currents allow for high welding speeds     Applications   * >8mm; Not for sheets below 8mm * Commonly used for bridges and rails | |
| Advantages | Disadvantages |
| 1. High currents yield high welding speeds 2. Can join thick sections with a single pass (for low C steels, nickel, non-ferrous metals and their alloys) 3. Automatic feed of electrode and flux 4. Molten flux forms protective coating over weld, hence eye shield is not needed | 1. **Needs a lot of space** 2. Expensive 3. **Automation is necessary** |

* 1. **Metal and tungsten inert gas welding**

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| Metal inert gas welding |
| * Arc welding, but with inert gas shield to protect the weld joint from the atmosphere. * Often automated. In manual version, welding gun is used to feed electrode (filler) and deliver inert gas. * Inert gas is often He (if on ceiling), Ar (if on ground), mixed if somewhere in air. Cheaper versions include Nitrogen or CO2, but not perfectly inert.     Applications   * For confined spaces * For stainless steels, Mg, Al, Cu and Ti alloys. Without inert gas shield, will corrode * **Automated and faster than TIG** |
| Tungsten inert gas welding |
| * Same as metal inert gas welding, except no metal is deposited from tungsten electrode (non-consumable). Separate filler rod is thus needed.   Applications   * For thin to moderate sections (1-5mm). cannot be <1mm. * For stainless steels, Mg, Al, Cu and Ti alloys |
| Applications of MIG and TIG: inert gas shielding of stainless steels |
| * For Mg, Al, Cu and Ti alloys. Without inert gas shield, Cu, Mg and Al oxidise rapidly to form brittle oxides. Ti will form titanium carbide, oxide, nitride. * For stainless steels – inert gas shield will prevent formation of porous chromium oxide layer |

* 1. **Friction welding**

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| Friction welding |
| Mechanism   1. Rotating shaft that is chucked in a lathe is pressed against a stationary metal blank 2. Friction generated heats up the shaft/blank interface 3. When the rotation stops, metallic joint cools and welds together     Applications   * To join dissimilar metals (e.g. Cu to Al, Cu to steel, Al to bronze etc.) * Fast, usually below 30s * For welding *round* sections that can be clamped in a rotating chuck e.g. shafts, pipes |

* 1. **Resistance welding**

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| Resistance welding |
| Mechanism   1. Electrodes press the parts together and carry electricity through the points of contact 2. As electrode is a good conductor of electricity and (ideally) workpiece is poor, concentration of heat at workpiece joint, resulting in welding of joint     Applications   * Welding sheet metal of roughly the same thickness and material, as two different types of metals may lead to weld defects and galvanic corrosion. * Ideally, electrodes should be of low resistance and workpieces of high resistance to concentrate heat on workpiece. P = I2R * Fast, localised heat, no filler metal needed, **easily automated for large scale production**   Disadvantages   * High initial equipment cost * Difficult to join sheets of different thickness * For overlapping sheets, for poor conductors e.g. steel, mild steel (which doesn’t need inert gas shield) * Difficult for good conductors (e.g. Al, Cu, Ag). For these materials you often see rivets/screws. |
| Types of resistance welding |
| Spot welding: resistance welding of one spot at a time   * Problem with spot welding aluminium: Al is a good conductor, Al oxide formed hinders electrical conduction, copper electrodes alloy easily with Al, so copper electrode wears easily   Seam welding: to form a water-tight or air-tight seal, spot welds can be overlapped to form a continuous seam |

* 1. **Laser and electron beam welding**

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| Laser beam welding |
| * Short pulses broadly focused for wide shallow welds * Long pulses sharply focused for deep narrow welds     Applications   * For welding fine wires, thin foils in electronics industry which are inaccessible by other methods * For welding jobs requiring extremely high precision (e.g. micro spot welding) |
| Electron beam welding |
| * Short pulses broadly focused for wide shallow welds * Long pulses sharply focused for deep narrow welds * Tiny heat affected zone (0.1mm)     Applications   * For welding turbine blades. Done in vacuum with negligible risk of oxidation. * Losing popularity due to need for troublesome vacuum |

1. **Casting**

## **3.1 Sand casting**

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| Casting | |
| All metal is initially cast into either *ingots* (blocks) or continuously cast into endless *billets*.  Give a *parting line* rather than a *seam* as in welding. | |
| Sand casting | |
| The most primitive method of casting and uses expendable sand molds.  Patterns   * A mould is made using a pattern of the approximate shape of the casting. * Patterns wear out with use the dimensions become inaccurate. * Soft wood patterns are used to produce a small number of castings, hard wood patterns are used for large number. Metal patterns are used for producing thousands of castings.   Sand cores   * Sand cores are ‘removable’ cores (like an inverse of a mould) that are used to produce cavities inside a casting (core in casting) or gap on te outer surface of a casting (core on casting).   Process     1. Fill the ‘drag’ portion (lower part) of the flask (overall cast) with sand and a thermosetting binder. 2. Place the pattern I position. 3. Fill the ‘cope’ potion (upper part) of the flask with sand and a thermosetting binder, and place sand cores if necessary. 4. Heat the flask to harden the binder and hence the mould 5. Separate the cope from the drag to remove the pattern and the sand cores. 6. Re-assemble the cope and the drag and pour molten metal into the runner cavity and allow the metal to cool and solidity. 7. Break the sand mould to remove the casting and remove sand cores.  * Grain size and properties can be controlled by adjusting cooling rate. Slow cooling yields large grains, fast cooling yield short/fine grains.   Applications   * For any metal, so long as there is a furnace to melt it and the molten metal can flow easily (e.g. cast iron, steel, alloys of Al, Cu, Mg, Zn, Sn) * Stainless steel has poor fluidity in molten state because of high Cr content, making it hard to cast. High carbon content tends to mean better fluidity in steels (e.g. cast iron) | |
| Advantages | Disadvantages |
| * No limit to size of mould, can be used to produce huge parts (e.g. statues) * Cheap * No directional properties, isotropic * Complicated shapes can be produced, and can often produce almost finished shape | * Rough surface finish due to sand mould, though finer sand can help * Each mould can only produce one casting, very slow * Poor dimensional tolerances because metal shrinks on solidification and shrinks further on cooling from melting point to room temperature |
| Defects | |
| Caused by badly prepared pattern, poor design or poor casting technique.   1. Blow hole: due to cavity at cope surface, formed by evolved gas which cannot flow through the mould and collects as bubble at high point. Could be steam or carbon dioxide evolved from mould surface because of high moisture or organic content of sand mould.      1. Scar: a shall blow. Occurs on a flat surface, whereas blows occur on a convex surface.      1. Blister: a scar with a tin layer of metal covering it      1. Porosity: very small holes uniformly dispersed throughout the casting, present within the dendritic network of the cast microstructure      1. Drop: irregularly shaped projection on cope surface, results from a cavity formed in the cope surface when a lump of sand breaks loose from the cope. Happens when strength of mould before curing by heat (green strength) is too low and cannot take any small vibration of the cope. Loose sand will cause dirty and defective casting.      1. Inclusions and dirt: harmless if well dispersed in metal, bad only if in large quantities or concentrated at certain locations, which may weaken the cast material      1. Wash or cut: low projection in the drag occurring in bottom-gated castings; Too much metal flows through gate and moulding sand is not hard enough, resulting in erosion and drop-like effects as sand becomes dirt in casting and shape is defective. | |

## **3.2 Die casting**

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| Die casting |
| * Also called permanent mould casting, since permanent metal mould is used instead of expendable sand mould. Can be used for mass production to produce 1,000 to 100,000 castings. * Produces parts with best surface finish and tolerances second only to investment casting * Production rate is high and yields superior properties if die pressure is high enough and maintained long enough during metal solidification   Applications   * Better dimensional tolerances because metal solidifies under applied pressure. But still not good for very tight tolerances (e.g. screw threads) * Better surface finish because dies have smooth surfaces * Ideal for low-melting-point metals (Al, Zn, Pb, Cu, Mg and Sn alloys). * Iron based alloys (grey cast iron, malleable iron, low C steel, alloy steel, SS) have high melting points and require dies made of tungsten carbide, sintered molybdenum (high resistant to oxidization and thermal cracking) or graphite (cheaper but tends to oxidise and is less wear resistance) * Thin walls of 1mm are achievable; since molten metal is forced into cavity under high pressure, much thinner sections can be cast than in die casting * Parts must be simple enough that they can drop out in one direction (no tunnels), though can apply sand cores to die to create channels that can be knocked out   Dies (moulds)   * Usually made of medium C tool steel * Water cooled during use to prolong life and shorten casting time |
| Hot chamber die casting |
| * Metal is melted in an induction furnace, then forced into a die through and injection tube that keeps metal hot throughout * Part casts then drops * Cycle time is less than 1 minute. Automated casting can produce up to 15/min.     Applications   * For low melting point metals only (Pb, Sn, Zn alloys) that do not react with the steel walls of the injection tube at high temperature – Al, Cu and Mg tend to do so. |
| Cold chamber die casting |
| * Molten metal is poured in by robot arm. It starts to solidify though not completely as it is pushed through unheated cylinder into the die cavity. * Cycle time is less than 1 minute, automated die casting can produce:   + Up to 3/min for Al alloys   + Up to 5/min for Mg alloys   + Up to 2/min for Cu alloys   Advantages over hot chamber method   1. Can be used for non-ferrous metals of higher melting point (Al, Mg, Cu) 2. Liquid metal is in contact with injection cylinder walls for short time, resulting is less alloying with steel equipment |

## **3.3 Centrifugal casting**

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| Centrifugal casting: for hollow objects |
| Process   * Sand mould imparts shape * Rotation of centrifuge flings molten metal to walls, which is then cast as it solidifies     Applications   * For casting large pipes and cylindrical shapes * Often for parts that prefer solid part rather than seaming   Advantages   * Finer grain size because of fast cooling, creating tougher material * Cleaner castings can be produced because lighter non-metallic impurities segregate toward inner radius where they can be machined off * Highly dense structure, mostly free of defects * Automation possible * Can cast large pipes accurately |

## **3.4 Continuous casting**

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| Continuous casting |
| Process   * Metal is melted in a Tundish (furnace) and then allowed to solidify in a water-cooled mould. Cast metals moves down continuously at a rate controlled by take-up rollers.     Applications   * To make blooms, billets and slabs without having to cast ingots first – ie. continuously casting shape desired straight from melted metal * Continuously cast metal can also immediately be hot rolled into products after solidification. * For Cu and its alloys, all types of steels, Zn, Al and its alloys and cast iron * Often for reprocessing of scrap metal   Advantages   * Fully automated * Moulds/dies are relatively cheap * For recycling * Physical properties and surface finish are usually adequate for immediate application * Quick and convenient process to prepare metals for secondary hot-working operations straight from scrap metal |

## **3.5 Investment casting**

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| Investment casting | |
| Process   1. Create expendable die    1. Using a permanent die, inject was into die cavity under pressure to create wax pattern desired. Combine several wax patterns using heated spatula to create intricate patterns as desired, forming a ‘tree’. Sometimes polystyrene or frozen mercury is used instead of wax.    2. The wax ‘tree’ pattern is dipped into a slurry of very find silica, ethyl silicate and water, alcohol or other organic fluid. Known as investment slurry. Finer the silica, better finish, more expensive.    3. Increase thickness of coating over pattern by continuing to dip into successively courser sand until layer is think enough to form the mould wall (3-6mm).    4. Place in an over to dry, cure and harden the sand mould. Wax pattern will simultaneously melt off and drain out, leaving behind mould cavity of intricate pattern. Make sure to drain off all wax to obtain good casting, as any wax left behind will cause defects in casting. 2. Pre-heat now-formed investment mould to near melting point of metal that is to be investment cast, ensuring complete filling of mould activities (since metal will not cool and block) 3. Pour molten metal into cavity, let cool and solidify. Break mould to extract casting.   Applications  To obtain very intricate shapes with very good surface finish | |
| Advantages | Disadvantages |
| * Extremely good surface finish, finer silica used, smoother the surface of castings * Can cast very complex shapes (e.g. jewellery, tooth fillings, surgical instruments, statues, aircraft parts, etc.) * No need to machine subsequently, especially beneficial for steels and hard alloys that are difficult to machine * Wide range of alloys suitable – steels, bronze, nickel-based alloys, titanium, magnetic materials, stainless steels * Close tolerances despite need for cooling | * Expensive * Castings cannot be too large |

1. **Powder Metallurgy**

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| Powder metallurgy | |
| Applications   * High melting point metals that are difficult to forge (e.g. cutting tools from aluminium oxide, silicon carbide, silicon nitride, tungsten carbide, Titanium carbide, Ceramics, Cermets, CBN etc.) * Final product has laminar or composite structure, or is porous/controlled density * Minimum thickness about 1mm, maximum thickness about 2.5D   Process  **Blending/mixing**   * For pure metals, concern revolves getting right size distribution * For multiple metals, to ensure right proportion of metals mixed * Inclusion of lubricant here if self-lubricating material is intended outcome – stearic acid, paraffin, zinc stearate etc. * Time needed usually 30-60 minutes * Size of particles usually 20-30 μm (but can be as small as 1μm. Particle shapes range from sphere to flake, depending on method of powder production. * Reducing atmosphere necessary to prevent surface oxidation, which can be explosive in the case of certain metals that have highly exothermic oxidation processes.   **Compaction (pressing)**   * Usually cold pressing done, but hot pressing done for harder materials by passing a current through it. * Compression ratio usually ranges 2:1 to 3:1 for Fe and Cu, up to 8:1 for harder materials. * Compression pressure ranges 75 to 1500 MPa, hard powders need higher pressures * Rate of compaction can be as fast as 1/s for small parts using mechanical presses; large parts require hydraulic presses * For ductile materials, pressure creates cold welds so that no binder is needed. * For hard materials, holding force between particles is mainly due to interlocking effect between irregular surfaces of the particles, so a binder is needed to make the compact self-supporting.   **Adjustment of porosity and density during compaction**   * During compaction, areas of contact are increased, green strength (pre-sintered) increases due to mechanical locking and cold pressure welds.      * Pressure of compaction can be adjusted to control porosity (and thus density). * Theoretically, if a powder is pressed enough, it should attain 100% density and strength of the parent metal after sintering. In practice, porosity ranges 10% to 90%. Often 30% for bearings.     **Sintering**   * Heating of PM compact, normally done in a reducing or neutral atmosphere or vacuum oven to prevent oxide films from forming and to increase the interatomic forces between particles * Sintering temperature ranges 70-90% of melting points, above recrystallisation temperature * Some undesirable localised melting may take place * Duration can range 30 minutes to several hours     **Other secondary processes**   * Grind, machine or press forge to achieve accurate dimensions and properties * Infiltrate with another metal of lower melting point to reduce brittleness (e.g. iron, MP of 1537C, with copper, MP of 1083C) * Impregnate with oil by:   + Boiling PM part in oil to remove air from pores and replace with oil. Does not evacuate all the air.   + Use vacuum suction to evacuate the air from pores and introduce air into pores. Evacuates almost all air, but more difficult and expensive.   Metal powders available today   * Most common: Fe, Cu, Al, W, Ni, Co * Less common: Mo, Ag, Au, Pt, Pd, Ti, Zr, Mn, Sn, Zn, Cd, Sb, Bi, Si, V, Te, Be; bronzes, stainless steels, high speed steels * Others: tungsten carbide, cermets, ceramics, stellites | |
| Isostatic pressing (optional, normally to create high-performance materials – not a general use case) | |
| * Usually done hydrostatically, hot or cold * Hot pressing yields higher density, lower porosity. * Cold pressing yields lower density, higher porosity. | |
| Methods of producing metal powders | |
| 1. Atomisation: molten metal is forced through a small orifice and a stream of compressed air, steam or inert gas is directed upon it to break it up into fine powder. For any metal whose melting point is not very high; most popular method of producing PM powders. 2. Electrolysis and mill grinding: metal is deposited electrolytically, then milled or grinded into fine powder. Often for Fe, Cu, Tantalum 3. Reduction of compounds: grind oxide and pass reducing gas (H2, CO) at high temperature. For Fe, W, Ni, Mo, Co, Cu 4. Form pellets by pouring molten metal through a sieve then mill/grind pellets into powder 5. Precipitate the metal powder from solution. For Zn, Ag 6. Vapor condensation: vaporize metal and allow vapor to condense. For Zn 7. Shotting: drop molten particles from a small opening through air or inert gas into water. Produces spherical particles but not smallest sizes. 8. Granulation: stir molten metal vigorously during solidification to break it into tiny powders | |
| Advantages | Disadvantages |
| 1. High melting point metals can be fabricated below their melting points – only commercially viable way to fabricate tungsten (MP 3400C), tantalum (MP 3000C) and Mo (MP 2600C) 2. Non-metallic constituents can be introduced, and their contents controlled 3. Special structural effects:    1. Controlled porosity and density    2. Can create lamellar (alt. layer) structure    3. Can create composite structure 4. Good dispersion in alloys 5. High purity of metal 6. Machining often not necessary 7. Close tolerances (±10μm) 8. No waste material 9. High speed production for small part (compacts about 1/s) 10. Uniform composition | 1. High cost of raw materials (powders, dies, equipment). Scale of production normally >100,000, not worth cost if <10,000 2. Dies in pressing must be very simple since powders cannot flow around corners. Complex shapes need several punches, otherwise density will not be uniform. Can be overcome by using powder injection moulding. 3. Size of product limited by size of dies. Usually products <15kg. 4. Storage of powders is difficult as they have very high surface area to volume ratio and tend to oxidise. Need to be stored in vacuum or non-oxidising atmosphere. 5. Powder size may not be consistent., often statistically distributed. 6. Products of PM could be brittle since porosity lowers tensile strength, ductility and fatigue endurance. 7. Difficult to hand low melting point metals as they tend to melt when sintered. 8. Slight shrinkage on sintering and cooling to room temperature. 9. Cannot be bent or cold-worked subsequently due to brittleness |

1. **Pipe and tube production**

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| Pipe and tube production |
| Decision depends on:   1. Wall thickness 2. Diameter 3. Length 4. Application |
| Medium performance pipes |
| Induction welding of cold rolled strip |
| Process   1. Metal is cold rolled intro a strip, known as a skelp 2. Strip is bent between rollers to form a tube 3. Longitudinal seam is welded by induction welding, during which the tube is separated from the induction coil by a nylon sheet     Applications   * Not for tubes below 10-15mm * Not for good conductors of electricity like Al, Cu, brass * To make low cost and low strength tubes of various steels (mild steels and stainless steels), weld joint is a discontinuity that limits strength of tube. * Most common method of making steel tubes of circular, square and rectangular cross section – to make non-circular cross sections, simply cold roll round tubes into shape using rollers on four sides. * Hypodermic needles made this way need a secondary process of cold drawing with a mandrel first, and later without a mandrel when the diameter gets too small. |
| Drawing and pressing of sheet |
| Applications  For making very small tubes of thin wall thickness |
| Seam welding of metal strip |
| Same as induction welding, but depending on tube size seam can be welded by:   * Hot pressure welding * Electrical resistance welding * Submerged arc welding   Applications  For large pipes |
| Roll bending and welding |
| 1. Roll bend thick metal strip into pipe 2. Weld seam using submerged arc welding   Applications  For very thick and very large pipes. |
| Spiral welding of metal strip |
| Process   1. Cold rolled metal strip 2. Joined spirally by arc welding or submerged arc welding     Applications  For making extremely large pipes |
| Welded from separate metal sheets |
| Applications  For making extremely large pipes |
| High performance pipes |
| Hollow extrusion |
| * For making high-performance seamless tubes and pipes, large hole with thin walls. * For highly conductive metals eg. Al, Cu, brass |
| Mannesmann process |
| Process   1. Heat a round rod (billet) and pass it between two tapered rollers to open a central hole. Central hole is opened as rollers cause a bi-axial tensile stress at the centre of the billet. 2. Pierce hole with a stationary mandrel that is free to rotate while feeding the red-hot billet forward   Applications   1. For making reliable tubes and pipes of *any* size that must not have a welded joint 2. Generally, for **small hole in a very thick wall. Normally for heavy duty tubes, but can go down to 100mm diameter.** |
| Casting with a central core |
| For cast iron pipes (corrosion resistant) of any size. This is because cast iron pipes are too brittle to be manufactured by other forming methods. |
| Centrifugal casting |
| For very large pipes of cast iron and steel, and other metals. |

1. **Material removal processes – Machining**

## **6.1 Overview of machining**

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| What is machining? |
| A manufacturing process in which a sharp cutting tool is used to cut away material to leave the desired part shape. The predominant cutting action in machining involves shear deformation of the work material to form a chip; as the chip is removed, a new surface is exposed. |
| Advantages and disadvantages of machining |
| Advantages   * Able to work with a variety of work materials – plastics, composites, metals, some ceramics * Able to create a variety of part shapes and geometric features * Able to achieve high dimensional accuracy * Able to create very smooth surfaces – roughness >0.4µm   Disadvantages   * Wasteful of material * Time consuming (relative to forging, casting etc.)   Cutting conditions |

## **6.2 Theory of chip formation**

|  |  |  |  |
| --- | --- | --- | --- |
| The orthogonal cutting model | | | |
| The model   * Two dimensional analysis of three dimensional process, not a single point tool * Uses a wedge shaped tool perpendicular to direction of cutting speed * Cutting edge is perpendicular to direction of cutting speed * Two elements of tool geometry are rake angle and relief/clearance angle   Key angles and dimensions     * **Shear plane angle ϕ**; angle between plane of shearing and horizontal * **Rake angle γ**; determines direction that the chip flows * **Clearance angle α**; provides small clearance between flank face and work surface * **Length of shear plane *ℓ0*** * **Thickness of chip *tc*** * **Original thickness of chip *t0*. Equal to feed in turning.** * **Width of cut, equal to depth of cut in turning.**   Ratios   * **Cutting ratio, rc** = * **Chip thickness ratio, r** = * **Relationship between chip ratio r, Rake angle γ and shear plane angle ϕ:** | | | |
| Mechanism of chip formation in the orthogonal cutting model | | | |
| 1. As the tool is forced into the material, the chip is formed by shear deformation along a plane (the shear plane). 2. At the sharp cutting edge of the tool failure of the material occurs, causing separation of the chip from the parent material. 3. Along the shear plane, where the bulk of the mechanical energy is consumed during the machining, the material is plastically deformed.   Approximation of turning via the orthogonal cutting model     * The orthogonal model can be used to approximate turning and certain other single-point machining operations so long as the feed in these operations is small relative to the depth of cut | | | |
| Actual chip formation | | | |
| * Shear deformation process does not occur along a plane, but within a zone. If shearing were to take place across a plane of zero thickness, it implies that shearing action must occur instantaneously as it passes through the plane. But since zone is often very thin, there is no significant accuracy loss. * Secondary shear occurs from friction between the chip and tool as the chip slides along the rake face. | | | |
| Types of chips | | | |
| Discontinuous chips | Continuous chips | Continuous chips with built up edge | Serrated chips |
| * Often with brittle materials at low cutting speeds * Tends to impart irregular texture to machined surface * Occurs with high tool-chip friction and large feed/depth of cut | * Occurs with ductile materials at high speeds and relatively small feeds and depths * Good surface finish results * Encouraged by sharp cutting edge and low tool-chip friction * Long continuous chips can cause problems with disposal and tangling; tools are often equipped with chip breakers | * Ductile materials at low to medium speeds * Friction between tool and chip causes portion of work material to adhere to rake face of tool * Formation of BUE is cyclical; forms, grows, becomes unstable and breaks off. Sometimes takes portion of tool rake face with it, damaging tool. Portions of BUE not carried off with chip are embedded in work surface, affecting finish | * Cyclical chip formation of alternating high and low shear strain * Mostly from hard-to-machine materials like titanium allows and other hard materials * Can also occur with common work metals when cut at high speeds |
|  | | | |
| Forces acting on the chip in metal cutting | | | |
| * **Normal force** on chip surface gives rise to **friction force** between rake face and chip; **resultant force R**, **friction angle β** * **Shear and normal forces** induced in chip in response; **resultant force R’**   Shear stress   * Shear stress acting along plane between work and chip is stress required to perform machining operation. * Equal to shear strength of material under conditions of cutting.     Shear strain  Shear deformation along the shear plane can be approximated by a series of parallel plates sliding against one another to form the chip after failure.     * is shear plane angle, is rake angle, α is clearance angle | | | |
| Forces acting on the tool that can be measured | | | |
| * None of the four force components can be directly measured because the directions in which they are applied vary with different tool geometries and cutting conditions. * Cutting tool can be instrumented using dynamometer (force measuring devices) so that force components acting against the tool can be measured – **cutting force and thrust force**.     Relating forces on chips to measurable quantities Fcutting, Fthrust and tool rake angle and shear plane angle  *Ffriction = Fcutting sin +Fthrust cos*  *N = Fcutting cos – Fthrust sin*  *Fshear = Fcutting cos – Fthrust sin*  *FN = Fcutting sin + Fthrust cos*  *Fcutting = Fshear cos – FN sin*  *Fthrust = Fshear cos + FN sin* | | | |
| The Merchant equation and force circle | | | |
| Merchant force circle   * Derived on the principle that the chip, tool and surface are in equilibrium, so R = R’ = R’’. * Shear force deviates from Fcutting by shear plane angle, since Fcutting is parallel to horizontal * Ffriction is parallel to rake angle since it acts on rake face * N deviates from R by friction angle     Merchant equation     * A chip is produced when minimum shear energy is achieved – where sufficient mechanical force is applied beyond which shear stress is enough to form chips. At all other possible shear angles, shear stress is less than shear strength, so chip formation cannot occur. * There is a minimum shear plane angle at which shear stress required is minimal. By taking the derivative of shear stress with shear plane angle, we can find this minimum shear plane angle. | | | |
| Implications of the Merchant equation | | | |
| We can control the shear plane angle by changing the rake angle and friction angles (and coefficient of friction).   * Rake angle can be controlled by tool design * Friction angle can be reduced by using lubricant * If all other factors remain same, higher shear plane angle = smaller shear plane area = lower shear force and energy required for machining. | | | |
| Assumptions of the Merchant equation | | | |
| 1. Chip behaves as a rigid body in equilibrium 2. Chip remains straight and has infinite contact length on the rake 3. Force transmits across the tool-chip interface and shear plane 4. There is no extra force acting on the tool edge and flank face 5. Shear angle is the product of minimum work to produce a chip | | | |

## **6.3 Power and temperatures in machining**

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| Power | Unit power a.k.a. specific energy per unit time |
| Pc = RMR \* specific energy | Specific energy: the amount of energy required to remove a unit volume of material  Power per unit volume rate of metal cut     * Chip thickness before cut t0 also affects the specific energy and unit horsepower. As t0 is reduced, unit power requirements increase – referred to as the size effect. * E.g. grinding – small chips compared to other operations – has very high specific energy values * Need to apply correction factor to values of specific energy, as values are based on 0.25mm undeformed chip thickness. **U’ = CF × U or from graph** |
| Cook equation: Analytical methods to compute cutting temperatures | |
| * Most often measured in practice using thermocouple. * 98% of energy in a machining operation is converted to heat | |

## **6.4 Classification of machined parts**

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| Rotational vs prismatic (non-rotational) parts |
| Rotational   * Cylindrical or disk-like shape * Geometry produced by cutting tool removing material from a rotating work part (e.g. turning and boring)   Prismatic   * Geometry created by linear motions of the work part combined with rotating or linear tool motions (e.g. milling, shaping, planning, sawing) |
| Generating vs forming |
| The operations that create part shape are classified as generating and forming.  Generating: Path followed by tool during its feed motion determines part shape. Cutting conditions include speed, feed rate, depth and width of cut.    Forming: Cutting edge of tool has reverse of shape to be produced. Depth of cut refers to final penetration into the work, cutting conditions include primary speed and feed motion.    In some scenarios forming and generating are combined in one operation – like thread cutting on a lathe. |

## **6.5 Turning and related operations**

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| Turning |
| * Single-point tool removes material from surface of a rotating workpiece * Tool is fed linearly in a direction parallel to axis of rotation to generate a cylindrical geometry * Traditionally carried out on a machine tool called a lathe |
| Cutting conditions in turning |
| Important dimensions:   * D0, uncut diameter of part * Df­, final diameter of part * L, length of cylindrical work part   Cutting conditions   * fr , near feed rate(mm/min) * f, Feed (mm/rev) (chip thickness before cut) * N, Rotational speed (rev/min) * v, cutting speed (m/min) * d, depth of cut * Tm, machining time * RMR, volumetric material removal rate (mm3/min)       Surface finish   * Higher v, smaller f, larger nose radius will result in better surface finish |
| Operations related to turning |
|  |
| Boring |
| * Uses a single point tool like turning but performed on the inner diameter of an existing hole rather than outsider diameter of existing cylinder. * Horizontal boring can be done in two ways: boring bar fed into rotating part, or work is fed past rotating boring bar (can be done on lathe). * Vertical boring is done for large, heavy work parts with large diameters; usually D > L.   Boring bar   * Must be very stiff to avoid deflection and vibration during cutting. * Often made from cemented carbide, E = 620 GPa |
| The engine lathe and methods of work holding |
| Methods of work holding    Can carry out:   * Boring, drilling, turning |
| Other lathes and turning machines |
| * **Turret lathe:** manually operated lathe in which tailstock is replaced by a turret with up to six cutting tools. Able to quickly switch between different tools, used for high-production work that requires a sequence of cuts. * **Chucking machine:** uses chuck in its spindle to hold the work part. Tailstock is absent, so parts cannot be mounted between centres – restricting use to only short, light-weight parts. Automatic, operator only loads and unloads. * **Bar machine:** chucking machine, but collet is used instead of a chuck. Allows for long bar stock to be fed through headstock into position. At the end of each machining cycle, a cut off operation separates the new part. Automatic. * **Automatic screw machine:** bar machine used in the production of screws. * **Multiple spindle bar machine:** a bar machine with multiple spindles that can work on multiple parts at a time, often each with different types of cutting tools. Allows for very high production rate. By moving through sequence of cuts. * **Screw machine:** allows a very long bar stock to be used * **Horizontal turning machine:** typically used for work parts in which length is greater than diameter ie. the regular lathe. Vertical turning machine is opposite. * **Mill turn centre vs turning centre:** mill turn centre can position a cylindrical work part at a specified work angle so that a *rotating cutter* can machine features into the outside surface of the part. |

## **6.6 Drilling and related operations**

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| Drilling |
| * Used to create a round hole in a work part * Tool is often a rotating tool with two cutting edges, called a drill bit. * Typically performed on a drill press, but can also be done on a lathe   Anatomy of a drill bit |
| Cutting conditions in drilling |
| Important dimensions:   * D, diameter of drill bit * d, hole depth measured from surface to deepest point with full diameter **for blind holes** * t, part thickness **for through holes** * A, approach allowance that accounts for drill point angle; the distance drill must feed into work before reaching full diameter * Θ, drill point angle   Cutting conditions   * fr , near feed rate(mm/min) * f, Feed (mm/rev) * N, Rotational speed (rev/min) * v, cutting speed (m/min) * Tm, machining time * RMR, volumetric material removal rate (mm3/min) |
| Operations related to drilling |
| Can improve tolerance on hole diameter. |
| Drill presses |
| * **Upright drill:** regular drill press mounted on floor * **Bench drill:** small drill mounted on table or bench rather than floor * **Radial drill:** large drill press to cut holes in large parts * **Gang drill:** 2-6 upright drills connected in an in-line arrangement, operated independently. Allows for drilling operations to be completed in sequence. * **Multiple spindle drill:** allows for multiple holes to be drilled simultaneously * **CNC drill press**   Work holding for drilling: jig and fixtures   * **Fixture:** holds piece down, designed to guide workpiece into the right position quickly * **Jig:** attached to fixture, guides the tool to the right positions |

## **6.7 Milling**

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| Milling |
| * Machine operation in which a work part is fed past a rotating cylindrical tool with multiple cutting edges * Axis of rotation of cutting tool is perpendicular to direction of feed * Tools: milling cutter with teeth * An interrupted cutting operation; teeth of milling cutter enter and exit the work during each revolution, subjecting teeth to a cycle of impact force and thermal shock on every rotation |
| Peripheral milling |
| Axis of tool is parallel to surface being machined. Also includes plain milling.    Down vs up milling |
| Face milling |
| Axis of cutter is perpendicular to the surface, machining performed by cutting edges on both the end and outside periphery of the cutter. |
| Cutting conditions in milling |
| Important dimensions:   * D, diameter of tool * d, depth of cut * A, approach distance required to fully engage cutter * L, workpiece length   Cutting conditions   * fr , near feed rate(mm/min) * f, chip load (mm/tooth) * nt, number of teeth on cutter * N, Rotational speed (rev/min) * v, cutting speed (m/min) * Tm, machining time * RMR, volumetric material removal rate (mm3/min) |
| Milling machines |
| Orientation type   * Horizontal milling machines: for peripheral milling * Vertical milling machine: for face, end, surface contour, die sinking milling   Machine type   * Knee and column: basic * Bed type * Planer type * CNC * Machining centre: often for drilling and milling |

## **6.8 Other machining operations**

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| Shaping and planing |
| Both use single-point tools moved linearly relative to the work part. Differ in which moves. Shaping: a single-point tool moves linearly past a stationary work part     * Time taken = L/ number of passes × time per pass * Time per pass = forward time + backward time + acceleration times |
| Broaching |
| Performed using a multiple tooth cutting tool by moving it linearly relative to the work in the direction of the tool axis. Can do external and internal broaching. For internal broaching, a starting hole is needed. Teeth progressively change from roughing to finishing, often changing in diameter. |
| Cut-off operations: Sawing |
| Process in which a narrow slit is cut into the work by a tool consisting of narrowly spaced teeth. |
| Creating screw threads |
| External threads   * Single point treading (turning) * Cutting with a threading die * Thread milling * Self-opening threading die: thread chasing     Internal threads   * Tapping * Collapsible tapping |
| Creating gears |
| * Gear form milling: most appropriate for low quantities. * Gear hobbing: a type of milling operation. * Gear shaping * Gear broaching |

## **6.9 High speed machining**

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| Requirements for high speed machining |
| * Special bearings for high rpm * High feed rate capability (e.g. 50m/min) * CNC motion controls with ‘look ahead’ features to avoid undershooting or overshooting tool path * Balanced cutting tools, toolholders and spindles * Coolant delivery that provides higher pressures * Chip control and removal systems to cope with high metal removal rates * DN ratio: bore diameter of the spindle bearing **multiplied** by the maximum spindle speed |

1. **Machining: Cutting tool technologies**

## **7.1 Tool wear and tool life**

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| Tool wear |
| Tool failure   * **Fracture failure:** cutting force at the tool point becomes excessive, causing failure by brittle fracture * **Temperature failure:** cutting temperature too high for tool material, causing tool point to soften and plastic deformation and loss of sharp edge. Can be avoided by using only for finishing operations (decrease d, f, increase v) * **Gradual wear:** gradual wearing causes loss of tool shape, reduction in cutting efficiency and acceleration of tool wear as tool becomes heavily. Will experience tool failure similar to temperature failure at end of life.   Types of tool wear   * **Crater wear (main):** cavity in rake face that forms and grows from action of chip sliding against surface. Extent can be measured by depth or its area. * **Flank wear (main):** occurs on flank face of tool, results from rubbing between newly generated work surface and flank face near cutting edge. Measured by width of wear band. * **Notch wear:** an extreme case of flank wear occurring when the original work surface is harder and/or more abrasive than the internal material (which could be caused by previous machining or cold drawing, sand particles in the surface from casting etc.). Wear is accelerated in this region as a result. * **Node radius wear:** type of flank wear that occurs on the nose radius leading into the end cutting edge. |
| Wear mechanisms |
| Abrasion   * Causes but flank and crater (rake) wear * Chips generated from work material that contain hard particles that act like grinding wheels with fine cutting edges slide over tool faces, causing abrasion * Inclusions like carbides, oxides and nitrides that are harder than tool materials contribute to this.     Adhesion   * Tool-work interfacial temperature increases through frictional sliding in addition to high pressure. Soluble atoms of the tools can adhere to the work material across the interface (welding). Adhesion causes formation of built-up-edges. * As BUEs grow and become unstable, they tear off, scratching the work surface and chipping away tool material surface.     Diffusion   * Tool-work interfacial temperature increases, and soluble atoms of the tool diffuse into the work material across the interface. * Exchange of atoms causes tool surface to become depleted of atoms responsible for its hardness, accelerating wear. * Principal mechanism of crater wear.     Oxidation   * Reaction between tool face and oxygen with high temperatures and clean surface leads to formation of oxidised layer on tool. * Oxidised layer is softer and can be sheared away, exposing new material to sustain the process. * Commonly happens when machining steel with HSS or Tungsten Carbide tools. * Severe groove damage can result if oxygen concentration is high. Often solved by using inert gas and coolant.   Repeated plastic deformation (fatigue)   * Takes place when surfaces sliding against each other under high contact pressure. * Interlocking of surfaces due to roughness leads to compressive and tensile forces that can plastically deform the cutting edge, making it more vulnerable to abrasion of the tool surface. |
| Tool life |
| Tool life  Length of cutting time that tool can be used. Most often operation till tool reaches a certain value of flank wear is used, since it is risky to use till failure as it could damage the work surface or cause unpredictable processes halts.  Tool lifespan  General relationship of tool wear vs. total cutting time can be represented by three regions: break-in, steady-state and failure.     * **Break-in period:** sharp cutting edge waers rapidly at beginning of its use, often within first few minutes of use. * **Steady-state wear region:** relatively uniform wear rate * **Failure region:** cutting temperatures are higher and general efficiency of machining is reduced. If allowed to continue, tool will fail by temperature failure.   Slope of tool wear curve in steady-state region is affected by work material and cutting condition (speed, feed, depth of cut). Harder material, higher speed, feed, depth of cut all increase slope. |
| Taylor tool life equation |
| Basic tool life equation   * v: cutting speed * T: tool life * n: relative constant for a given tool material * C: constant that depends on tool material, work material and cutting conditions   Extended tool life equation  Extended version that includes effects of feed, depth of cut and work material hardness.  , cutting speed effect dominates feed and depth of cut |

## **7.2 Tool materials**

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| Material needs |
| * **Toughness:** to avoid fracture failure, tool material must have high toughness, usually characterised by high strength and ductility. * **Hot hardness:** material must be able to retain its hardness at high temperatures. * **Wear resistance:** wear resistance depends on surface finish of tool, chemistry of tool etc., aside from hardness due to different mechanisms of wear. |
| Cast cobalt alloys |
| * Typically contain Co (40-50%), Cr (25-35%) and W (15-20%) as its main ingredients * Made into desired tool geometry by casting, after which cutting edges are ground to final size and sharpness * Wear resistance is better than HSS but not as good as cemented carbide * Toughness better than carbides but not as good as HSS * Hot hardness between HSS and carbides * Application between HSS and carbide, higher v than HSS, higher f than carbides |
| High speed steel |
| Properties   * Highest toughness, lowest hardness * Max cutting speed of about 50m/min @ 600C * Manufactured through hot working and powder metallurgy * Often coated with TiN through physical vapor deposition to improve cutting performance * Basic types are based on Mo and W * Edges can be heat treated to achieve hardness levels as high as Rockwell C65   Types  Largely divided into two groups: tungsten-type (T grades) and molybdenum-type (M grades). Tungsten types contains W as its principal alloying ingredient, though additional alloying elements include Cr and V. M grade HSS contain W and Mo, plus some additional allotting elements as in T grades. |
| Cermets |
| Cermets are defined as composites of ceramic and metallic materials.   * Cermet in industry generally refers to combinations of TiC, TiN and TiCN with Ni or Mo as binders. * High hardness, thermal stability and deformation resistance; good hot hardness and oxidisation resistance * Higher speeds are generally allowed with these tools compared with steel cutting carbide grades. * Applications for finishing through medium to light cutting, but due to shock resistance not suitable for heavy machining. Mostly for high-speed finishing and semi-finishing of steels, stainless steels and cast irons |
| Cemented carbide |
| Cemented carbides are technically cermets, but ceramic-metal composites containing TiC, TiN and other ceramics are known as carbides in industry.   * Class of material formed from tungsten carbide (WC) using powder metallurgy with cobalt as the binder * Divided into two basic types: non-steel cutting (WC-Co only) and steel-cutting grades (WC-Co with additions of TiC and TaC)     Properties   * Have high compressive strength but low-to-moderate tensile strength * High hardness and hot hardness * Good wear resistance * High thermal conductivity * High modulus of elasticity (600 GPa) * Toughness lower than HSS   Significance of WC grain size  Non-steel cutting grades   * Suited for machining aluminium, brass, copper etc. (non-ferrous metals). But, can machine cast iron. * Typical grain size found here range between 0.5 to 5μ. As grain size increases, hardness and hot hardness decrease, but tranverse rupter strength increases.   Steel-cutting grades   * Used for low carbon, stainless and other alloy steels. * As Fe absorbs WC at high temperatures, TiC or TaC are added/substituted for some WC-Co in the composite as TiC and TaC have low solubility in Fe. This improves the tool’s resistance to crater wear and edge deformation. However, it decreases flank wear resistance.   Applications |
| Coated cemented carbide |
| A cemented carbide insert coated with one or more thin layers of wear resistant material such as TiC, TiN or Al2O3­.  Properties:   * Serve as diffusion barriers (low solubility in Fe) and provide additional abrasion resistance, improving tool life and enabling higher cutting speeds * TiC and TiCN have high hardness and improve abrasion wear. * AL2O3 and TiAlN have high heat resistance and thus high oxidation resistance, reducing thermal wear.   Coating process    Combining properties of coatings: multilayer transitional coatings on carbide   * Thin TiC as contact layer to WC-Co * TiCN as transitional layer to TiN since adhesion of TiN has bad adhesion on WC-Co. Alternating layers of TiN and Al2­O3 as TiN supports Al2O3 since laminated structure is less sensitive to brittle failure compared to a two-layer system. |
| Sintered Polycrystalline diamond and cubic boron nitride |
| SPD   * Very high cutting speed and hardness, high thermal conductivity, lower thermal expansion * Graphitisation at above 700C * Chemical affinity with ferrous metals and nickel-based alloys mean applications to high speed machining of non-ferrous metals and abrasive non-metals (fiberglass, graphite, wood) * Manufactured by heating graphite with catalyst and fusing together in a mass, or fine-grain diamond crystals * Softer than natural diamond   CBN   * Second hardest material after diamond, stable at high temperatures (<1000C) and applicable to ferrous materials * Hexagonal crystal structure like diamond * Applications in hardened steel when WC speed is limited * High thermal conductivity, thermal stability, oxidisation resistance * Can be reinforced with TiC or TiN |
| Ceramics |
| Properties   * Composed largely of fine-grained Al2O3 pressed and sintered at high pressures and temperatures with no binder into insert form. * Very high hardness, no chemical affinity with work material, so applicable to hardened steel * Very brittle – sensitive to shock and limited to finishing applications * good applications for surface finishing very hard materials   Reinforcing elements   * ZrO2 (2-5%): increases fracture toughness but retains wear resistance; applications to cast iron * TiC (30-40%): increase hot hardness but reduces toughness; applications to finishing hardened steel * SiC (25%): increases toughness and reinforces structure, applications to Ni based superalloys |
| Summary of materials |
| Taylor tool life equation: typical values of n and C    Material properties |

## **7.3 Single point tools**

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| Single point tool geometry |
|  |
| Chip breakers |
| Used with single point tools to force the chips to curl more tightly and fracture. Two primarily types – groove types (in the tool itself) and obstruction types (an additional device on rake face). |
| Cutting edge and inserts in single point tools |
| Three primary ways of holding and presenting the cutting edge for singe point tools: a solid tool, brazed insert and mechanical clamped insert. Mechanically clamped inserts often have multiple cutting edges, and can be rotated (indexed) when one edge wears out and reclamped, making it more cost effective.    Inserts   * Various shapes have different properties. Generally having more cutting edges is more cost effective.      * Cutting edges are rarely 100% sharp as they represent extremely high stress points. Some preparation is thus done to the edge. |

## **7.4 Multiple cutting edge tools**

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| Drills |
| * Twist drills      * Straight flute drills (relatively large holes)      * Gun drills (deep holes)      * Spade drills (large diameter holes)      * BTDA drilling (very long, large and deep holes) |
| Milling cutters |
| * Plain milling cutter: Cutting edges are usually oriented at a helix angle to reduce impact on entry into the work.      * Form milling cutter * Face milling cutter      * End milling cutter |
| Broachers |
| * Broach consists of a series of distinct cutting teeth along its length. * Feed is accomplished by the increased step between successive teeth on the broach, rather than a relative feed motion. * Tool material removed in a single pass of the broach is the cumulative result of all the steps in the tool * Speed motion is accomplished by the linear travel of the tool * Shape of cut is determined by the contour of the cutting edges on the broach, particularly the final cutting edge. * Most are made of HSS |
| Saw blades |
| * Saw blades are defined by tooth form (geometry features), spacing, set. * Gullet allows space for the formation of the chips by the adjacent cutting tooth * Set type permits the cut by the saw blade to be wider than the width of the blade itself - otherwise the blade would bind against thewalls of the slit made by the saw due to friction |

## **7.5 Cutting fluids**

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| Functions |
| Reduce friction at tool-chip interface and remove heat from the process.  Coolants   * Specific heat and thermal conductivity are most important properties * Most effective when used on high speed steel   Lubricants   * Operate by extreme pressure lubrication – the formation of thin solid salt layers on metal surface through chemical reaction with the lubricant. These are more effective than conventional lubrication that uses thin liquid films between the two surfaces. Reduces friction and temperature. * Cutting oils provide the best lubricating qualities. |
| Application methods |
| * Flooding – direct stream of fluid * Mist application – high speed mist carried by pressured air stream, often for difficult-to-access areas * Manual application   Cutting fluid filtration and dry machining   * Cutting fluids become contaminated and lose performance – need replacement or a filtration system * Dry machining can be used due to environmental concerns and costs around disposing old fluid |

1. **Machining: Economic and product design considerations**

## **8.1 Machinability**

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| Machinability rating of a material |
| Machinability rating is with reference to B1112 Steel at 1.00. The score depends on six factors: tool life, tool wear, force, power, temperature and MRR.   * Higher score, material easier to machine     Good machinability   * Ease of chip disposal * Good surface finish * Long tool life (most important) * Low cutting forces * Material properties:   + Low ductility, low hardness   + Low tensile strength   Notes   * Aluminium has the lowest specific energy relative to brass, cast iron and steel |
| Achieving surface finishes |
| General process capabilities    Surface roughness in turning: mechanism     * Find ratio of actual/theoretical roughness based on material and cutting speed (see graph) * Sub into theoretical equation, solve   Reasons for not being able to achieve ideal surface roughness   * Built up edge effects (deposits) * Damage to surface caused by chips curling back into the work; can be reduced by using cutting fluids to reduce friction climbing with coolant texture reservoirs      * Tearing of surface when machining ductile materials: BUE contains hard particles that build up to flank face and scratch workpiece      * Cracks in surface when machining brittle materials caused by discontinuous chip formation * Friction between tool flank and new work surface, causing mechanical depression from the contact |

## **8.2 Machining economics**

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| Selecting depth of cut and feed rate: constraints |
| Depth of cut   * often predetermined by the workpiece geometry and operation sequence. * In roughing operations, depth is made as large as possible within the limitations of available horsepower etc. * In the finishing cut, depth is set to achieve the final dimensions for the part.       Feed rate  The appropriate feed depends on four factors:   * Roughing or finishing * Constraints on feed due to machine tool capabilities in roughing: high feed as possible, but given max depth of cut, there will be constraints on feed * Tool material      * Surface finish requirements |
| Optimising cutting speed for maximum production rate |
| Having fixed feed and depth of cut based on other factors, we now determine cutting speed for maximum production rate. |
| Minimising cost per unit |
| Disposable inserts vs regrindable tooling, different Ct    Total cost |

## **8.3 Design for machining**

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| Rules for machining |
| 1. Avoid machining if possible 2. Reasonable tolerances      1. No sharp corners (inaccessible for tools) or edges (burrs) – chamfer or fillet      1. No deep holes (L/D > 10) – large holes also require larger tolerances 2. Use standard stock 3. Don’t machine parts with high aspect ratio (they have no rigidity) – large and flat, thin and long 4. No undercuts unless absolutely necessary      1. Design part with minimum steps for machining      1. Dimensions with standard cutting tools      1. Only request multiple surface finishes when absolutely necessary 2. Consider machinability 3. Economies of scale |

1. **Unconventional Machining**

## **9.1 Electrode discharge machining**

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| Electrical discharge machining | |
| * Slow manufacturing process which will not normally be employed for mass production * Relatively standard process in tool and die industries | |
| Die-sinking EDM | |
| Process   1. Tool and workpiece are both immersed in a dielectric fluid (ionised fluid of high electrical resistance) 2. Potential difference causes ionisation of dielectric fluid through which electrons flow, causing a spark (like lightning) 3. Spark strikes workpiece at very high speed, heats up and vaporises some material, leaving a crater in the workpiece surface 4. Servo controls the movement of the electrode to maintain a constant gap to the workpiece (15-500μm), otherwise the gap will increase as the workpiece is eroded.     Notes   * If workpiece is positive and tool is negative, workpiece gets eroded faster if both are same material. Polarity may be changed at will. * Increased removal rate may also increase tool wear * Electrode tip temperature ranges from 8000C to 16000C.   Applications   * For making blind or through holes with perpendicularly straight walls and internal profiles like mould cavities. * To machine moulds and dies for die casting, plastic moulding, wire-drawing, extrusion, PM compaction, forging, piercing etc. * Male electrode to produce female electrode and steel die. Female electrode to produce steel punch.      * To drill small holes/slots that are too small for conventional tool bits * To machine materials that are too hard for conventional machining (e.g. sintered tungsten carbide, hardened tool steels) * To machine thin-walled parts that are too weak to withstand cutting forces of a conventional tool (e.g. aluminium sheets in honeycomb) | |
| Wire-cut EDM | |
| 1. Workpiece and wire-electrode from spool are immersed in dielectric fluid 2. Wire traces desired profile and machines in the same way as die-sinking EDM     Notes   * Wire is usually brass, copper or tungsten of diameter 30-200μm * Wire typically only can be used once   Applications   * For machining hard, conductive materials * For precision machining (e.g. teeth on gears below 1mm in diameter) * For machining complicated profiles e.g. bevels * For through holes and walls can be inclined at any angle, since process is computer controlled. | |
| Advantages | Disadvantages |
| 1. Can machine any hard material so long as it is conductive 2. Burr-free products 3. Close tolerances; dimensional accuracy improves as current is decreased. Can go below 1μm. 4. Can machine intricate configurations – narrow slots (30 μm), blind cavities, small ad deep holes (0.1mm diameter, up to 20D deep) 5. No mechanical strains induced in workpiece 6. Can produce sharper corners than conventional machining – 0.05-0.1mm radius | 1. Only for electrically conductive materials 2. Slow and not for large scale production 3. Because of stray material that cools and deposits when EDM stops, recast surface layer is formed. Recast layer has high residual stresses and roughness (matte surface finish). To improve finish, either reduce removal rate or add abrasive particles into EDM fluid. 4. Electrode wear could lead to poor dimensional tolerances |

## **9.2 Electrochemical machining**

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| Electrochemical machining | |
| Works by opposite principle of electroplating. Faraday’s law applies.   1. Tool acts as cathode, workpiece as anode. Electrolyte flows and sweeps away discharged material. 2. Tool movement is controlled by automatic servo mechanism.     Notes   * Metal removal rate is proportional to current, irrespective of hardness (Faraday’s law) * Faster removal rate than EDM * Unlike EDM, no damage to workpiece due to heat affected zone due to no heat * Components that contact electrolyte must be made of corrosion-resistant material. Use only neutal salts like NaCl, NaClO3, NaNO3   Applications   * For difficult-to-machine alloys (e.g. high Ni or high Cr steels, Ti, Be, hardened steels) * Often for:   + Aircraft engine components   + Airframe components   + Die making   + General machine parts   + Complex cavities (die, embossed surfaces, blind holes, through holes, square holes, complex external shapes, sharp corners)   + Rapid deburring   + Transformer cores   + Pump impellors   + Gears | |
| Components | |
| Power supply unit   * Most costly part of ECM machine * Converts AC to low DC of 5-30V * Current ranges from 50 to 10,000A * Generally needs about 1000 for every square inch of metal to be removed   Electrolyte   * Must have good electrical conductivity * Removes sludges of metal oxides or hydroxides formed during deplating process * Prevents overheating of electrodes   Electrode tool   * Negligible tool wear (no erosion). A single tool can produce thousands of parts * Tool-workpiece gap ranges from 25 to 125μm * Properties of a good electrode tool:   + Good thermal and electrical conductivity   + Cross-section large enough to conduct current   + Made of machinable material   + Resist chemical reaction with electrolyte   + Rigid enough to withstand distortion or vibration caused by high-pressure electrolyte flow (2.5MPa)   + Accurate dimensions   + Cutting surfaces must be polished for good results in the workpiece | |
| Advantages | Disadvantages |
| 1. Burr-free finish 2. No residual stresses 3. Can make very thin sections with very little distortion 4. Can make odd-shaped parts 5. No metallurgical damage due to heat 6. Very long tool life | 1. Very expensive equipment 2. Need accessories (water, steam, electrical systems), complex operation |
| Chemical machining | |
| Same as electrochemical machining – but electric current is not used. Metal removal is by chemical dissolution using a chemical reagent or etchant (acid or alkali). Only parts of workpiece to be removed are exposed, while the rest are protected by masking. | |

## **9.3 Electrochemical grinding**

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| Electrochemical grinding |
| A special kind of electrochemical machining where cathode is a rotating grinding wheel.  Mechanism of material removal: 90% electrolytic action, 10% mechanical abrasion.    Grinding wheel: diamond particles bonded together with metals such as brass, Cu or Ni  Role of diamond particles   * Abrade from workpiece surface any non-conducting oxides/inclusions * Act as insulating spacer between workpiece and grinding wheel, thereby maintaining a proper gap between the two electrodes (prevents arcing)   Applications   * An alternative method to grind sintered carbide parts, usually cutting tools   Advantages   * Good surface finish * Good tolerance * Low mechanical and thermal stresses on workpiece * No surface cracks * Tool life as long as tools in conventional means |

## **9.4 Laser beam machining**

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| Laser beam machining | | |
| Process   * Laser is focused through a lens to provide a beam spot on the workpiece, workpiece part is melted and vaporised (All metals and non-metals may be vaporised) * Gas jet of air, oxygen or inert gas like nitrogen or argon may be used (optional)     Functions of gas jet   * Provide oxidising atmosphere so that surface oxidises, and reflectivity is reduced by up to 85% - light absorption increased * Provide heat necessary for machining – 80% of heat required for cutting comes from exothermic oxidation reaction * Carries away slag and removes unvaporised steel from path of the beam   Common types of lasers   * Solid state e.g. ruby (crystalline Al2O3), sapphire, or YAG (yttrium-Al-garnet) * Gas lasers e.g. argon or CO2 * Liquid lasers (not for industrial use or machining) * Semiconductor lasers (not for industrial use or machining)   Laser energy modes   * Pulsating – 1,000 to 10,000 pulses per second (to chip away discrete holes or lines on workpiece) * Continuous   Advantages   * Excellent tolerances (1μm per mm) * Can drill holes as small as 5μm diameter, as deep as 50D * Holes drilled are burr-free * Minimal distortion due to heat from heat affected zone * No deformation on workpiece due to tool pressure | | |
| Applications | | |
| Micromachining | Medical | Others |
| * VERY small holes, eg. holes in rubber baby milk-bottle nipples, holes in thin-wall fibreglass tubes, holes in nylon buttons, holes in needles, holes in nozzles | * Micro-surgery * “spot-welding” of bone fractures, retinas * Alter chromosomes without killing cells * Tattoo removal * Holes in contact lenses * LASIK | * Cutting metal slabs * Fast and automated cutting of patterns from multi-layer stacks of fabrics * Trimming flash * Photo-etching (fast, inexpensive) * Engraving |

## **9.5 Electron beam machining**

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| Electron beam machining | |
| Process   1. Electrons accelerated by potentials of 100-200kV up to 0/75c 2. Electron beam focused by electromagnetic lenses 3. Impact of beam on workpiece causes workpiece part to melt and vaporise by virtue of KE converted to heat   Applications   * Micro-machining of thin materials * Precise high-speed drilling of circular holes (150μm diameter, 1.25mm thick) * Welding | |
| Advantages | Disadvantages |
| 1. Workpiece is protected from oxidation since it is in a vacuum 2. Fast and precise metal removal | 1. Needs a vacuum, sealing is a problem and it limits part size 2. Deep holes have tapered sides 3. Vaporisation of metal makes it difficult to maintain vacuum 4. Operators must be shielded from generated x-rays   Slowly being phased out by laser beam machining. |

## **9.6 Ultrasonic machining**

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| Ultrasonic machining | |
| Process   1. Workpiece and tool both submerged in abrasive slurry 2. Transducer converts high frequency electrical power into mechanical energy by vibrating metal tool 3. Abrasive grains are bounced off by tool and erode away small particles of workpiece (impact machining) 4. Tool is fed down into workpiece as material is abraded away     Notes   * Amplitude of tool motion ranges 15 to 100μm * Wear rate is proportional to hardness of workpiece. Harder material, faster machining * Vibrating cutting tool is made of soft materials (e.g. brass, soft steel, copper) to keep its wear rate low * Tool is driven at resonant frequency to achieve large amplitude of vibration to impart proper cutting force to abrasive particles   Abrasives used: Boron carbide, aluminium oxide, silicon carbide | |
| Applications | |
| * For machining hard, brittle materials like ceramic, germanium, glass, cemented carbides, gemstones * Can perform milling, drilling, surface grinding, threading, cavity sinking, engraving and lathe-type operations | |
| Advantages | Disadvantages |
| * Does not alter metallurgical, chemical and physical properties * Excellent surface finish can be achieved by using very fine abrasive grit * Excellent tolerance | * Not suitable for soft materials * Sidewall taper caused by tool wear and secondary impact in gap between tool and workpiece * Very slow, use only when other methods fail |

## **9.7 Abrasive jet machining**

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| Abrasive jet machining | |
| Principle: uses high-velocity stream of abrasive particles to remove metals  Particles used: Al­2O3 or Silicon Carbide  Gas:   * air, nitrogen or CO2 at 200-900kPa * nozzle jet can be manual or automated * nozzle must be abrasion resistant (made of tungsten carbide or synthetic sapphire) * nozzle diameter between 0.1 to 2mm   Sand blasting vs abrasive jet machining | |
| Applications | |
| To machine materials sensitive to heat damage (ie. when LBM, EDM, EBM cannot be used).   * Slice thin sections of hard, brittle materials * To etch * Remove broken tools from holes * To produce frosted/matte finish * Clean mould cavities * For deburring e.g. hypodermic needles * To remove flash and parting lines from moulded plastic parts | |
| Advantages | Disadvantages |
| 1. No heat effects (done at rtp) 2. No mechanical contact between tool and workpiece 3. Can machine materials of high hardness 4. Good tolerance (below 5μm per mm) 5. Best way to machine intricate shapes in hard brittle materials | 1. Abrasives cannot be recycled because they lose their sharp edges, tend to contaminate and clog up system 2. Only for machining hard materials as abrasives get embedded in soft materials 3. Removes only small amount of material 4. Workpiece must permit access of nozzle |

## **9.8 Plasma arc machining**

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| Plasma arc machining | |
| Similar to tungsten inert gas welding except that shielding is by ionised hot gas, rather than inert gas.   * Gas is usually argon/nitrogen mixture * Specially designed torch confines gas to an arc column where it ionises * Very high temperatures (33,000C) can be achieved. Able to concentrate a lot of heat at a point. * Filler rod is sometimes used   Applications   * For good conductors of heat * To cut any thick metal (up to 10cm) at high speeds e.g. 0.5m/min * For deeper, narrower welds at higher speeds than other arc-welding processes | |
| Advantages | Disadvantages |
| * Can cut with little metallurgical or physical damage * Fast welding * Very high temperature achievable, good for high conductivity metals (Al, Cu, Mg) * Good control of heat – can weld Al sheet below 0.5mm thick and stainless steel sheet of 25μm thickness | * Creates heat affected zone * Produces rough cutting edges |

## **9.9 Water jet machining**

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| Water jet machining | |
| * Uses high velocity stream of water as cutting agent. Water jet (up to 300m/s) acts like saw and cuts very narrow groove in the workpiece. * Pressure generally around 850MPa (exceeds yield strength of most steels) * Can generate pressures of up to 1400 MPa (limited by strength of nozzle and pumping equipment) * Nozzle diameter ranges 0.04 to 0.3mm, usually made of tungsten carbide * Sometimes abrasive particles (10 to 50μm) may be added to water jet to increase rate of removal   Workpieces   * Metals, polymers, fabrics, wood, paper, leather, brick, rubber etc * 0.8 to 25mm thickness | |
| Advantages | Disadvantages |
| * Cutting can start at any location * No heat involved, no heat affected zone * No deformation on rest of workpiece * Minimal burr * No replacement of cutting tools * Gives a smooth cut * Suitable for lightweight industrial robots since water jets produce little recoil or vibration | * Needs sophisticated pumping equipment because of high pressures involved * Needs nozzle of very high strength |

1. **Plastic technologies**

## **10.1 Plastics**

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| Plastics | |
| Thermoplastics   * Soften on heating, harden on cooling. Due to sliding taking place on carbon chains due to relatively weaker inter-chain links (imf, not cross-links) * Reversible process, scrap material can be recycled. * However, reheating may cause deterioration in the material * Make up most plastics in use today as easier to process than thermosets and more suited for large scale production * Do not have fixed melting point since they are never perfectly crystalline, soften gradually over a range of temperatures   Thermosets   * When plastic polymerises, cross-linking occurs between molecular chains and plastic forms a permanent rigid, hard and brittle mass. * Usually reinforced with fillers (composites) * Irreversible process * Can be used at higher temperatures than thermoplastics * Generally transparent or translucent but opaque when filled to form composites   All plastics will char or vaporise when heated to elevated temperatures due to decomposition of the polymer. | |
| Advantages | Disadvantages |
| 1. Wide range of colours 2. Good thermal, electrical insulation 3. Good corrosion resistance 4. Low density/specific gravity 5. Easy to process – usually no secondary process needed 6. Cheap 7. Flexibility can be adjusted using plasticisers 8. Can be made opaque using dyes | 1. Repairs using heat can never be perfect 2. May give off odours 3. Not for high temperature uses 4. Will creep (slowly plastically deform) under any load, resulting in permanent plastic deformation at any temperature 5. Weak under load unless reinforced 6. Subject to deterioration, especially in sunlight 7. Low stiffness (low E and G) |
| Joining plastics | |
|  | |
| Rough costing of major plastics in Singapore | |
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## **10.2 Thermoplastic resins**

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| Acetal (polyacetyl) |
| * Very high strength * Cannot stand boiling water   Applications   * Often used to replace metals in load-bearing components |
| Acrylic |
| * Most transparent plastic available, transmitting over 90% of light * Trade names are plexiglass, Perspex, lucite; chemical name is polymethylmethacrylate PMMA   Applications   * Transparent/translucent applications with reasonable rigidity * Resistant to solvents, acids, alkalis |
| Cellulosics |
| * Extremely cheap * Employs cellulose fibres from wood or cotton * Comes in many forms (e.g. cellulose nitrate - flammable, cellulose acetate, cellulose acetate butyrate, ethyl cellulose, cellulose propionate) * Transparent unless altered * Attacked by termites, since it is plant matter * Brittle, crack relatively easier   Applications   * Non-flammable applications, since cellulosics are flammable |
| Fluorocarbons |
| * Heaviest of all common plastics * Expensive * Can stand high temperature and corrosive environments * Low coefficient of friction and low surface energy (non-stick)   Applications   * Polytetraflouroethylene PTFE (Teflon is trade name) * Chorotriflouroethylene CFE * Mostly for coating for lubricating/non-stick uses in high-heat applications |
| Polyamides |
| Nylons   * Excellent toughness and wear resistance * Low coefficient of friction * Poor dimensional stability (tends to absorb water)   **Applications**   * Solid form used to replace metals in load bearing applications if dimensions are not critical (e.g. zippers) * In the form of fabric, often used for high strength fabrics and clothing * In foam form, it is used for sponges   Aramids   * Very high strength and stiffness   **Applications**   * Fibres (e.g. Kevlar) for reinforced wearables like helmets, bulletproof vests |
| Polyesters |
| * Produced by esterification reaction (organic acid + alcohol 🡪 ester + water   Polyesters and their applications   * Polycarbonate (PC): commodities that need impact strength and/or transparency e.g. cash cards. Transparent. * Polyethylene terephthalate (PET): cheaper but not as impact resistant as PC. Transparent * Polybutylene terephthalate (PBT): |
| Polyolefins |
| * Second **cheapest** plastic in Singapore * Corrosion resistant, waxy surface, non-toxic * Two main types: polyethylene PE (specific gravity ~1.0, cannot stand boiling water) and polypropylene PP (floats in water specific gravity ~0.9, stronger, more expensive, can stand boiling water)   Applications of PE variants   * LDPE: translucent, non-toxic, chemically very inert. **Commonly used for household and kitchen items**. * HDPE: hard, impact resistant, lasting. Common for toolboxes, water bottles. Opaque. * Ultra-high molecular weight PE: for very high wear resistant surfaces e.g. surgical implants. Higher density, so opaquer.   Applications of PP   * Non-toxic, high temperature resistance. For items that must withstand boiling water. E.g. kettle |
| Polyurethane (solid, n­on-foam form) |
| * Like a piece of rubber   Applications   * Replacement for rubber in components e.g. belt drives * Can be woven into fabrics |
| Styrenes­ |
| * Cheap, brittle, transparent * Non-toxic * Excellent for low and sub-zero temperature applications   Types and applications of styrene   * ABS (acrylonitrile butadiene styrene) is opaque, impact resistant, but cannot stand boiling water. Often for prototyping or toys. * SAN (styrene acrylonitrile) is transparent and can stand boiling water, but more brittle than ABS. often for transparent kitchen ware. * Solid polystyrene. Often for rigid items that are not load bearing but used in cold applications e.g. ice tray * Foam polystyrene (Styrofoam): packaging, insulation |
| Vinyls |
| * Polyvinyl chloride (PVC) is the cheapest plastic in Singapore * Cannot stand boiling water * Transparent unless dyed * Rigid and hard unless plasticised; some plasticisers are toxic and plasticised PVC should not be used for foodstuffs   Applications   * Vinyl can be foamed and used as cushion fillings * PVA (polyvinyl acetate) is a non-toxic re-sealable adhesive |

## **10.3 Thermosetting resins**

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| Amino plastics |
| * Hard surface * Wear resistant * Strong   Types and applications of amino plastics   * Urea formaldehyde: used for electric sockets, wood glue, surface tends to get stained * Melamine formaldehyde: stain resistant – thus used in dishware as replacement for ceramics, coatings for table tops. Melamine foam is used to make sponges. |
| Caseins |
| * Obtained from milk products * Obsolete and seldom used * High flexural strength, tough   Applications   * Mah-jong tiles |
| Epoxy |
| * High strength * Very corrosion resistant * Chemically very inert * Expensive * Tends to be brittle unless filled * Dimensionally very stable   Applications   * Adhesive – trade name is araldite. * Coatings for corrosion and abrasion resistance * Often filled with glass, carbon or graphite fibres to form composites e.g. helicopter blades |
| Phenolic |
| * Trade name is bakelite, chemical name is phenol formaldehyde * Extremely hard and brittle unless filled * Excellent chemical, electrical and heat resistance   Applications   * Mainly for heat and/or chemical resistance. E.g. handles for irons and cooking utensils |
| Polyesters |
| * Those that are thermosetting are usually used as a matrix for making composites e.g. fibreglass reinforced polyester * Good weathering characteristics and corrosion resistance   Applications   * Matrix for composites in outdoor applications e.g. boat hulls |
| Polyurethane |
| * Thermosetting formulation is usually used in foam form * More flexible than Styrofoam * More expensive * Used in place of natural sponge * Last much longer than Styrofoam * Good insulator   Applications   * Sponge and/or insulation that is flexible e.g. winter clothing lining |
| Silicone |
| * Can be used with fillers or without fillers * Soft and rubbery * Often used as a heat-resistant replacement for rubber if high temperatures (up to 500C) are encountered * Cures at room temperature in the presence of oxygen – convenient for large objects or joining/sealing   Applications   * Electrical insulation * Protective coatings * Dies for die casting low melting point metals |

## **10.4 Thermoplastic manufacturing methods**

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| Injection moulding |
| Process   1. Hopper is loaded with plastic resin in the form of grains 2. Resin is heated to soften it as it is fed through and Archimedean force (less wear and time efficient than a plunger as it would have to reciprocate up and down the tunnel) until it enters the mould cavity 3. Resin solidifies in water cooled mould 4. Mould is opened to release part     Applications   * Simple parts that can be moulded (opened on one side). Often only for simple shapes.   Mould technology and design   * Most expensive component of the cost of production (aside from installation of machine). **For large scale production > 10k** * Design carefully so that final plastic product can be easily ejected * Surface finish of product depends on mould surface finish * Usually made of Al, ASSAB 718 steel or STAVAX (for corrosive resins like PVC) * Cavities are often finished using EDM * Will have parting line |
| Blow moulding |
| Process   1. Extruded tube of thermoplastic (“parison”) is placed between jaws of a mould while still hot and soft 2. Mould is closed 3. Pressure from compressed air inside parison forces material against mould wall to form a hollow object 4. Mould opens to eject part. Leaves parting line.     Applications   * For making thin-walled hollow thermoplastic parts **that have an opening** e.g. milk bottles * Can also be more making very thin bags (e.g. PE bags), even thinner than calendaring. |
| Latest blow moulding technology |
| Injection moulded (rather than extruded) preform that looks like a test tube of the diameter of the opening is heated and ‘blown up’. Preform already has screwed threads/other details moulded in place during prior injection moulding.  Process   1. Injection moulding to form preform    1. Mould opens    2. Mould imparting shape of screw closes first    3. Injection moulding machine moves in, heats resin, feeds resin and forms test-tube preform    4. Resin solidifies, injection moulder moves away, leaving preform on the mandrel        1. Blow moulding    1. Mould imparting share of bottle body closes    2. Pressure from compressed air through mandrel forces material against mould wall to form hollow object while resin is still soft    3. Mould opens and ejects |
| Calendaring |
| Process   * Similar to rolling of metals – squeeze softened thermoplastic resin between rolls to form continuous thin film of sheet     Applications   * Thin films or sheets, thinner than those produced by extrusion e.g. shower curtains |
| Extrusion |
| Softened plastic is forced by a rotating screw or a plunger through a die, where it cools and solidifies.    Applications   * Rods, pipes, sheets of uniform cross section * Wire-coating extrusion * Thin films to be used alone and as coating for paper (sheets), cloth etc. * Fibres e.g. nylon fibres |
| Rotational moulding |
| Process   1. Place plastic resin in metal mould 2. Heat mould to soften plastic 3. Rotate mould about *two* perpendicular axes to spread resin evenly over the internal mould surface 4. Cool mould with water to solidify plastic part 5. Open and remove hollow part, remove flash at parting line   Moulds can be made out of aluminium.    Applications   * To create hollow, *generally* cylindrical parts * **Cheap but very slow** * **Not for large scale production, usually <100 pieces** |
| Thermoforming (of plastic sheets) |
| After calendaring, sheets can be subsequently formed into other shapes. |
| Match mould forming |
| Process  Similar to deep drawing of sheet metal.   * Heat plastic sheet * Form sheet between male and female moulds to give desired shape     Moulds usually made out of aluminium or steel, mounted on hydraulic or pneumatic press.  Applications   * Polystyrene trays * Ping pong balls (halves, later joined by adhesives) * Cannot for a part with holes (e.g. fan) |
| Vacuum forming |
| Process   1. Heat plastic sheet 2. Stretch sheet over female mould 3. Air is removed through small holes in female mould cavity, forming a vacuum between sheet and mould 4. Atmospheric pressure forces heated sheet against contour of female mould     Female mould often made of machined or cast aluminium or filled epoxy. Wood or plaster can be used for short production runs.  Applications   * **Cheapest of all thermoforming processes because male mould is eliminated** |
| Pressure/blow forming |
| Process   1. Heat plastic sheet 2. Stretch sheet over female mould 3. Air is removed through small holes in female mould cavity, forming a vacuum between sheet and mould. Simultaneously, air is pressurised. 4. Pressure forces heated sheet against contour of female mould   Applications   * One step up from vacuum forming, for moulding sheets that are too thick and require pressure that exceeds atmospheric pressure |
| Plastisol moulding |
| Plastisol – a mixture of finely ground resin (usually PVC) and plasticisers. Plasticisers are liquid at rtp but solidify at high temperature, usually above 180C.  Process   1. Parts to be coated are heated to 150C 2. Parts are dipped into liquid plastisol, then left to dry in an oven above 180C 3. Plastisol solidifies and form layer around part e.g. tool handles     Applications   * To coat wires with PVC or handles |

## **10.5 Thermoset manufacturing methods**

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| Compression moulding |
| Process   1. Measured quantity (20-30% excess of actual) of resin in a mould 2. Compact resin under heat 3. Molten resin fills cavity and hardens to permanent form (cross-linking). Will leave flash.     If a chemical hardener is available, cross-linking can take place without and/or pressure  Applications   * Good tolerances, much better than injection moulding. e.g. for prosthetics |
| Transfer moulding |
| Process   1. Solid resin preform is first put in a transfer pot where it is heated until it melts 2. Molten resin is forced from transfer port to mould cavity 3. Molten resin solidifies permanently in cavity     Advantages over compression moulding   * Products have no flash, at most parting line, and thus require less finishing * Can mould many products simultaneously using many runners from one transfer pot * Can mould small intricate parts which are difficult to compression mould |
| Reaction injection moulding |
| Process  A cross between injection moulding and compression moulding (hybrid process).   1. Two liquid components of a thermosetting resin are mixed and introduced in the mould cavity, using an injection moulding machine 2. Chemical reaction leads to cross-linking in mould   Applications   * Used for moulding rubber tyres |

## **10.6 Thermoplastic and thermoset manufacturing methods**

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| Casting | | |
| Process  Similar to casting of metals.   * Thermoplastics solidify in the mould on cooling * Thermosets solidify in the mould by chemical reaction   Moulds are cheap and often made of plaster, metal or plastics like silicone (temperature resistant)  Applications   * Slow process, for small scale production or making prototypes * Common casting resins are acrylic, thermosetting polyesters, silicone, epoxies, phenolics, thermosetting polyurethane * Cast thermosetting plastics are often filled with reinforcement * E.g. acrylic sheets and plates, tubing, rods, jigs, moulds etc. | | |
| Laminating | | |
| Plastic laminates consist of layers of plastic sheets or layers of paper, fabric, wood included with plastic.  Using thermosets   1. Layers of sheets or fabrics are impregnated with a liquid thermoset 2. Assemble layers to get required thickness 3. Apply heat and pressure (150-180C, 7-14MPa) to solidify laminate   Using thermoplastics  Same as using thermosets but must be allowed to solidify by cooling before removal.  Applications   * Tabletops, silent running gears, panels etc. | | |
| Reinforced moulding | | |
| Process   1. Saturate a woven reinforcing material with a thermosetting resin 2. Mould it (wrap around mould or squeeze many layers between moulds, compression mould) 3. Cure   Applications   * For making composites e.g. carbon fibre reinforced plastic * Polyester, epoxy and silicone can cure at rtp with chemical hardeners. Phenolic and melamine cure at 100-200C with machines. * Reinforcement materials are usually chopped glass fibres or carbon fibres in the form of woven mats of varying types of weave and thickness. | | |
| Foam moulding | | |
| Process  Add air or gas to plastic resin to form a sponge-like material. Can create rigid foam (Styrofoam) or flexible foam (e.g. PU, PVC, silicone, rubber) | | |
| Mechanical foaming | Physical foaming | Chemical foaming |
| Vigorously agitate the liquid resin until it forms a foam of air bubbles. Used to foam PVC plastisol. | 1. Force compressed gas into molten resin that is under pressure. 2. As pressure is released, gas expands and foams the plastic.   e.g. Styrofoam using CO2, foamed PE using Nitrogen gas | Mix or dissolve liquid resin in a chemical compound which will react under heat to form a gas.  Used to foam PU.  E.g. Expandable polystyrene EPS  CO2 gas producing reagents are incorporated in Styrofoam resin known as EPS. When injection moulded at 95C, reagents react under heat to give CO2 and foams the material. |
| Subsequent operations  Foamed plastics can be extruded, cast, vacuum formed, injection moulded etc, like normal plastics  Applications   * Floatation – reliable, cannot be punctured * Packaging – shock absorbent, light * Cushioning – for PVC, PE and PU foams * Insulation – for refrigerator linings, coffee cups | | |

1. **Additive manufacturing**

## **11.1 Basics of additive manufacturing**

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| Additive manufacturing process flow |
| STL file format  “Standard tessellation format”: representation in a computer of geometries of a CAD model. Can be then sliced into layers for Additive manufacturing system to manufacture. |

## **11.2 Additive manufacturing technologies**

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| Stereolithography and digital light processing |
| Both stereolithography (SLA) and Digital Light Processing (DLP) create 3D printed objects from a photopolymer resin by using a light source to cure the liquid material. SLA uses a laser, while DLP uses a projector.   1. Build platform is submerged into translucent tank filled with photopolymer resin 2. Light located inside machine maps each layer of the object through the bottom of the tank, solidifying the material 3. After the layer has been mapped and solidified , the platform lifts up and lets a new layer of resin flow beneath the object again 4. Process is repeated layer by layer until model is complete     Applications   * Highly accurate products with smooth surface finishes e.g. sculptures, jewellery molds, prototypes. * Not meant for large objects |
| Fused deposition modelling |
| 1. Line of solid material (filament) is guided from a reel attached to the 3D printer to a heated nozzle that melts the material 2. Once melted, the material is extruded on a specific and predetermined path created by the software according to the STL file 3. As the material is extruded, it instantly cools and solidifies, providing the foundation for the next layer of material until the entire object is printed     Properties   * **Cheapest 3D printing technology on the market** * Applicable to a wide variety of filament materials from plastics (e.g. ABS) to exotic materials e.g. carbon)   Applications   * Quick and low cost prototyping * Relatively low resolution, so not recommended for intricate designs |
| Selective laser sintering |
| 1. Printer has two beds called pistons – when the printing process begins, a laser maps the first layer of the object in the powder, which melts (sinters) the material. 2. Once the layer is solidified and bound, the print bed moves down slightly as the other bed containing powder moves up, and a roller spreads a new layer of powder atop the object 3. Process repeated and laser melts successive layers until the desired object has been completed     Properties   * Almost complete design freedom as excess unmelted powder acts as support for structure as it is produced, allowing for complex shapes to be manufactured with no added support needed. * Slow   Applications   * Industrial 3D applications for end products * Functional prototypes |
| Material jetting |
| 1. Printer jets liquid photopolymer onto build tray in a specific pattern. UV light instantly cures the photopolymer 2. Removable gel-like support material is jetted to support structure while printing. 3. Process is repeated until object is complete     Application   * Used in industry for rapid tooling and prototyping due to realistic and functional properties and fine details of products * Most precise 3D printing technology today, able to print up to 16 microns. Some advanced systems can use multiple jets that allow for combination of different polymers with different properties and colours. |
| Binder jetting |
| 1. Nozzle spreads binding agent across first layer of object in a specific pattern to bind the powder together 2. Once the first layer is fused, the printing bed moves down slightly and a thin layer of new powder is spread atop the object 3. Process repeats until object is complete 4. After completion, object is removed and cleaned and coated with an adhesive to give it strength     Properties   * Able to print in full colour * Able to print complex shapes without additional supports * Structurally not very strong   Applications   * Industrial 3D printing, most common material is full-colour sandstone (e.g. models and life-like sculptures) * Prototyping with colour |
| Selective Laser melting and electron beam melting |
| Two of the most common metal 3D printing technologies. Due to powder being metal with high melting points, they require much more power – so a high power laser (SLM) or electron beam (EBM) is used.   1. Machine distributes a layer of metal powder onto a build platform, which is melted by a laser or electron beam 2. The build platform is then lowered, coated with a new layer of powder and the process is repeated until the object is complete     Properties   * Support structures are required – they anchor the object and enable heat transfer away from the melted powder. * SLM takes place in a low oxygen environment and EBM in a vacuum, in order to reduce thermal stresses and prevent warping. * Technologies have evolved to a stage where prints are comparable to machined parts in terms of chemical composition, mechanical properties and microstructure.   Applications   1. Manufacturing – steel, titanium, aluminium, cobalt-chrome, nickel |
| Laminated object manufacturing |
| 1. Paper is used as the base material 2. Layers of adhesive coated plastic, paper or metal laminates are fused together and cut into shape with the aid of a knife or a laser cutter |

## **11.3 Materials for additive manufacturing**

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| General purpose plastics |
| * ABS and PLA are affordable, durable and widely available * Available in all colours and well-suited for prototyping mechanical parts and designs that don’t have a lot of overhangs * Models with outward facing wall angle sharper than 45 degrees can’t be printed without extra support * Parts under 1mm most likely won’t print   Applications   * Low-cost prototyping * Mechanical parts * NOT intricate designs |
| High detail resin |
| * UV-cured resin prints display fine details, sharp edges and have a smooth finish * Colour availability is limited but easily paintable * Can print up to 0.2mm   Applications   * Intricate designs and sculptures * Small, high detail models * Jewellery * Investment casting * NOT large models * NOT extensive exposure to UV light |
| SLS nylon |
| * strong, lightly flexible * slightly grainy finish, but can be polished   Applications   * functional prototypes and end products * complex designs with intricate details * NOT cavities |
| Fibre-reinforced nylon |
| * Designed for printing parts with strength of metal * Higher strength-to-weight than 6061 T6 Aluminium * Materials include carbon, Kevlar and fiberglass reinforced nylon   Applications   * Engineering parts * Custom end-use production parts * Functional prototyping and testing * Structural parts * NOT small parts with intricate details |
| Rigid opaque plastic (Vero) |
| * Smooth surface finish   Applications   * Realistic prototypes with fine-detail models * Form and fit testing * Sales and marketing models * NOT end products (sensitive to UV light) |
| Rubber-like plastic (Tango) |
| Applications   * Detailed models with various levels of flexibility * Soft-touch coatings, grips or non-slip surfaces * Fine details and smooth surfaces * NOT end products (sensitive to UV light) |
| Transparent plastic |
| * Clearest of 3D printing materials available   Applications   * Form and fit testing of see-through parts * Fine detail model building * Exhibition models or visualisation * NOT end products sensitive to UV light) |
| Simulated polypropylene |
| * Tough, flexible and durable * Good surface finish   Applications   * Tough and durable functional prototypes * Form, fit and functional testing * Flexible, snap-fit applications * NOT end products (sensitive to UV light) |
| Simulated ABS |
| * Designed to imitate ABS plastic by combining strength with high-temperature resistance * High impact resistance and shock absorption with good surface finish   Applications   * Molds * Tough and heat-resistant prototypes * Fine-detail models with smooth surfaces, form, fit and functional testing * NOT end products (sensitive to UV light) |
| Heat resistant plastic |
| Applications   * Hot air and hot water testing, heat resistant jigs and fixtures * Exhibition models that require strong lighting conditions * Tough and heat resistant prototypes * Fine-detail models with smooth surfaces * NOT end products (sensitive to UV light) |
| Full colour sandstone |
| * Best choice for photo-realistic, full colour prints * Does not allow for protruding features smaller than 3mm because material is brittle * Walls have to be wider than 2mm   Applications   * Architectural models, lifelike sculptures, gifts, complex models * NOT functional parts * NOT intricate features |
| Industrial metals |
| * For metal 3D printing   Applications   * Functional prototypes and end-use parts * Complex designs with intricate details * Mechanical parts * NOT cavities within design (unless making use of escape holes) |

## **11.4 Pros and Cons of additive manufacturing**

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| Pros | Cons |
| * Create complex designs at relatively low cost * High customisability * No need for tools and molds – lower fixed costs * Speed and ease of prototyping, faster and less risky route to market * Less waste | * Higher cost for large production runs * Less material choices, colours, finishes * Limited strength and endurance * Lower precision |
| Compared with subtractive manufacturing | |
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## **11.5 Key end users and trends**

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| Key end users |
| * Car manufacturers * Medicine and dentistry * Prosthetics * Aircraft manufacturers * Aerospace companies * Props * Product designers * Architects * Students * Design entrepreneurs * Engineers * Drone manufacturers * Shoes manufacturers * Consumer products manufacturers * Food * Humanitarian work |
| Nanoscale 3D printing |
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| Digitalisation: a part of the new way of manufacturing |
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**Notes**

1. Choosing manufacturing method:
   1. Material
   2. Dimensions
   3. **Shape**
   4. **Scale and cost**
   5. Functional needs
   6. Finishing