

**Engineering Tripos Part IIA 2006 Module 3C1**  
**Manufacturing Engineering Tripos Part I 2006 Paper P4A**

1. (a)(i) Different classes of processes essentially fulfil different functions (e.g. shaping, joining and surface treatment). Processes in different classes do not therefore compete with one another. The attributes which describe the capabilities of the process (technical, quality and economic) will therefore differ significantly between classes – requiring different record contents in the database. Material properties however are broadly universal to all materials, so a single database suffices.

(ii) Initial screening handles most technical requirements and some aspects of quality. Many design requirements are complex – the result of using a process is strongly coupled to details of the material being processed and/or aspects of the design detail. Examples:

*Shaping:*

- avoiding defects: the type of defect formed is sensitive to the process class (casting, forging, powder), varies from alloy to alloy, and depends on component details such as the aspect ratio of thin sections or changes in section.
- product properties, such as strength: very sensitive to alloy, particularly if a heat treatment forms an integral part of the shaping process (e.g. extrusion).

*Joining:*

- joint properties: strength and fracture toughness of welds depend on alloy (e.g. in steels, the hardenability), and the thermal history, particularly cooling rate (which depends on design features such as thickness, and process conditions such as power and speed).

*Surface Treatment:*

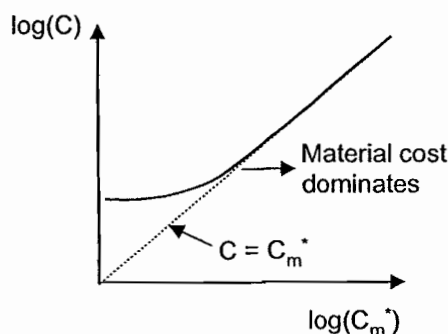
- wear resistance: depth and hardness of surface treatment is sensitive to process conditions and alloy used, and the consequent wear resistance depends in a complex way on service loads, environment etc.

(b)(i)  $C_m^*$  is the material cost per part (£), given by  $C_m^* = m C_m / (1 - f)$  where  $C_m$  is the material cost per kg,  $m$  the component mass, and  $f$  the scrap fraction in making each part.

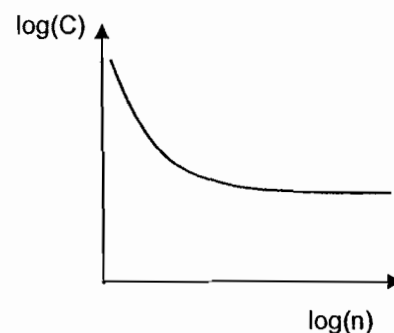
$C_t^*$  is the dedicated tooling cost (£), distributed per part by dividing by batch size  $n$ .

$C_{oh}^*$  is the overhead hourly cost (£/hr), distributed per part by dividing by the production rate  $\dot{n}$ .  $C_{oh}^*$  includes contributions of two types – (1) capital costs written off over a designated period, allowing for the proportion of time devoted to the manufacturing task in hand (giving an effective hourly rate for use of the equipment); (2) costs accumulated by the hour, principally labour, energy, and space.

(ii) sketch graphs:



1



1 (contd) (c) Supercooling is the depression of temperature of a melt below the local equilibrium melting temperature. Supercooling is required for nucleation of solid – typically by about 2 degrees for heterogeneous nucleation. Occurs at start of solidification, even for a pure material, and for only a short time until growing solid releases enough latent heat to raise temperature to melting point again. Results in rapid growth of dendrites: thin pieces of solid, in crystallographically-defined fast growth directions, which form the centres of grains as solidification progresses and the dendrite arms thicken.

Most alloys also experience *constitutional* supercooling, because the solid has different composition (higher purity) from the liquid with which it is in equilibrium. Results in liquid close to the growing solid carrying excess solute (impurity). Temperature gradient and solidification temperature gradient in this liquid are independent, and local temperature often dips below local solidification temperature. Condition may persist throughout solidification, but only in this small zone, which retains constant geometry as the liquid solidifies. Dendritic growth occurs, or cellular growth when the supercooled region is narrow.

(d) Homogeneous nucleation: atoms or molecules of material cluster together to form critical size nucleus within the body of the liquid. Heterogeneous: critical size nucleus forms on solid substrate of impurity (deliberate or accidental), or on container wall. Surface oxide frequently acts as heterogeneous nucleation site. (Homogeneous nucleation as such doesn't have significance (undercooling of 40-100 degrees), but the fact that pure materials can be undercooled without solidifying can be useful.) (i) A single crystal casting is achieved by very slow, controlled directional solidification from a single seed crystal, usually produced by the selective growth in preferred orientation via a spiral mould (pigtail) from the bottom of the casting. Heterogeneous nucleation from other sources/locations is avoided by the slow cooling rate which avoids significant undercooling except where desired. (ii) To achieve an equiaxed microstructure throughout an ingot, an inoculant is used, chosen to have a very small contact angle with the solidifying liquid to minimise critical nucleus volume (e.g.  $TiB_2$  in aluminium castings)

2. (a) (i) process to make metal powder with rounded shapes is gas atomization. Molten metal is forced through a nozzle and breaks up into drops under the action of a gas jet. The relatively slow cooling resulting from the air jet results in surface tension forces rounding the drops before they solidify, giving rounded particles. The gas will usually be inert (eg argon) to avoid oxidation of the metal.

(ii) processes to make metal powders with irregular shapes are water atomization and chemical reduction of oxide. Water atomization is similar to air atomization but uses water jet which cools the droplets much more quickly – they do not have time to become rounded. Reduction involves grinding of irregular particles of oxide, followed by reaction with a reducing agent such as hydrogen to produce metal, which will tend to have the same shape as the precursor oxide particles. A straightforward PM route involves powder blending (metal, alloy ingredients, organic binder, lubricant), compression in a shaped die to form a 'green' compact, possibly machining in the green state, sintering. Main influence of shape is in compaction, properties of green compact and in sintering. Rounded particles flow more readily and so fill the die better. They can pack better (provided the size distribution is correct) and so lead to higher density of green components. However, contact stresses between particles are greater for irregular particles and they therefore bond and

interlock better, giving higher strength green compacts. Greater surface area (for irregular particles) will give faster sintering.

(b) Uniform density will give more uniformity of strength, elastic modulus and other properties. Final density is directly related to density in the green state. Importantly, differences in density achieved during the compaction process will give different levels of residual stress which is relieved during ejection of the part from the die, and can then lead to cracking of the part due to differential expansion. Uniform density in a simple shape is aided by the use of lubricants (e.g. soaps such as calcium stearate) added to the powder blend, to reduce friction against the die wall and punch faces, and also for a more complex shape by the use of multiple (e.g. stepped) punches is essential so that different regions of the part experience similar extents of compaction. These methods are not applicable to HIPing as there is no die/punch system involved.

(c) (i) high porosity is useful in making filters and some bearings (high interconnected porosity needed to allow the passage of fluids or lubricants), and also in making materials which are to be infiltrated with a lower melting point material to produce a full density product (eg liquid metal infiltration).

(ii) a low MP additive will melt between grains and aid transport of material, speeding up diffusion and leading to more rapid sintering (liquid phase sintering)

(iii) smaller particle size means a greater surface area per unit mass and therefore greater driving force (in terms of surface energy change) for sintering. It also means shorter diffusion distances. Both effects lead to a strong dependence of sintering time on particle size.

3 (a) Critical cooling rate is the cooling rate above which a quenched steel will be 100% martensitic. Critical diameter is the diameter of a long cylinder which will form 50% martensite at the centre of the bar on quenching.

(b) X = start of transformation from austenite to ferrite; Y = start of transformation from austenite to martensite

(i) Extrapolating cooling rate scale, critical cooling rate is (very approximately) 10000 °C/min (167 °C/sec).

(ii) Critical diameters (50% martensite, 50% bainite): air 1 mm; oil 22mm; water 30 mm.

(iii) 10 mm diameter bar, centre microstructures:

air: 30% ferrite, 10% pearlite, 57% bainite, 3% martensite (approximate values);

oil: 100% martensite.

(iv) 270 HV at centre for oil quench and 600°C temper for 1 h, bar diameter = 50mm.

(v) Surface hardness as-cooled for 20mm diameter bars. For air, surface and centre hardness are essentially the same (same cooling rates due to poor heat transfer), hence

HV = 260; for water, surface hardness effectively left hand end of curve (very fast cooling rate), hence HV = 600.

(c) Hardenability is a measure of the ability of a steel to form martensite on quenching – no unique quantitative definition, but critical cooling rate, or distance along a Jominy end-quench bar at which 50% martensite forms, or critical diameter of a bar quenched in a given medium at which 50% martensite forms. Hardenability is influenced by steel composition: ie carbon content (the hardenability decreases to each side of the eutectoid composition) and by alloying (a large effect, with elements such as Mn, Ni, Cr and Mo making major increases in hardenability by slowing down the formation of carbides). Austenite grain size also has an important effect since ferrite and pearlite nucleate on the austenite grain boundaries. Fine grains give a large grain boundary area and so encourage rapid transformation i.e. give low hardenability. In welding it is desirable to avoid the formation of (brittle) martensite and so a steel of low hardenability is desirable. There is clearly an influence of the cooling rate which results from the welding process; for a process such as oxy-acetylene welding the cooling rate is low (as is the heating rate) whereas for laser welding it is much greater (perhaps by a factor of 1000). In order to avoid martensite formation in laser welding a steel of lower hardenability is needed than for oxyacetylene welding.

#### 4. *Pressure die casting and injection moulding*

(i) Similarities: material forced into split mould/die at high pressure.

Differences: Metal is fully liquid (v low viscosity) – injected via ram; polymer is viscous, semi-solid, and retains memory of processing in chain alignment – melted mixed and injected via extruder screw. Metal flow in mould is turbulent; polymer flow is mainly shear (some extension).

(ii) Metals: Low melting point; mainly zinc die-casting alloy, aluminium alloys.

Polymers: Any thermoplastic, or short-fibre thermoplastic matrix composites. Some thermosets can also be processed with care to ensure that they do not crosslink in the extruder.

(iii) Metals: Turbulent flow leads to porosity; can be reduced by casting under vacuum. Care must be taken to ensure that if there are separate streams of material in the die that they meet at high enough temperature to fuse properly and avoid cold shuts.

Polymers: distortion, surface sink marks, resulting from regions with different cooling rates (e.g. from different thicknesses) shrinking different amounts; reduced by

keeping screw in the forward position for longer (longer hold-on time). Crystalline polymers shrink more so present greater problems. Misruns (imperfect mould filling) - avoid by increasing injection temperature. Any polymer weld lines are sources of weakness.

(iv) Metals: More complex shapes can be produced by adding extra moving parts to a simple split die (e.g. an insert can be used to create internal cavities). Metal is rigid when removed from the die, so section walls usually slightly splayed; detail such as screw thread (for example) must be machined in afterwards.

Polymers: Still flexible when removed from mould, so shape limitations are more relaxed. Dimensional accuracy can suffer, though.

#### *Centrifugal casting and rotational moulding*

(i) Similarities: Closed mould rotated to produce layer of material on inner surface.

Differences: Centrifugal casting uses substantial steel hinged moulds and is used to make only simple shapes, usually cylindrical, rotated about a single axis. Mould fed with liquid metal once rotation is established.

Rotational moulding used to create larger range of shapes; thin metal (usually aluminium or steel) moulds used; heat supplied through mould walls (hot gas surroundings) to soften and fuse the polymer which is placed in the mould in granular form before rotation. Granules bond by softening and interdiffusion, but there is no gross melting. Rotation is usually about more than one axis

(ii) In principle all types of metals (often used for cast iron); thermoplastic polymers, often filled.

(iii) Defects – cold shuts etc as in any other casting process, irregularities of wall thickness – control by pouring/processing temperature + processing time for rotational moulding. Both processes give poor control of internal surface finish.

(iv) Centrifugal casting is limited to rotationally symmetrical shapes, often simple cylinders, whereas rotational moulding can form complex 3-D shapes (subject to ability to demould and correct flow of material within the rotating mould). Both processes limited to relatively thin-walled objects with no internal detailing.

(b) (i) polymers even in molten form have high viscosity and gravity pouring of molten polymer into a mould would not achieve adequate mould filling or surface

detail – application of very high pressure as in injection moulding would be needed and could not be achieved without destroying the investment. Further point is that removal of the hard ceramic investment mould is likely to damage the polymer component.

(ii) the viscosity of molten metals is so low that the process of film blowing could not be carried out – the film would collapse under gravity and surface tension forces before it could be inflated by internal gas pressure. The stability of the polymer film blowing process arises from a balance between gravitational forces, internal gas pressure, surface tension, chain alignment, viscosity, all as a function of temperature. The sharp melting point of a metal and lack of strength of its melt (no chains to align) make it impossible to achieve stable behaviour.

#### **Numerical answers**

3(b) (i) (very approximately) 10000 °C/min

(ii) air 1 mm; oil 22mm; water 30 mm.

(iii) air: 30% ferrite, 10% pearlite, 57% bainite, 3% martensite (approximate values);  
oil: 100% martensite.

(iv) 50mm.

(v) air, surface and centre hardness the same, HV = 260; water, surface hardness HV = 600.