

ENGINEERING TRIPOS PART IIA 2004

Solutions to Module 3C1
Materials Processing and Design
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Materials Processing and Design

Answers

Question 1

(a) All process selection involves consideration of technical suitability (can it be done at all?), quality assessment (can it be done well enough?) and process economics (can it be done cheaply enough?). Compatibility with material and cost are important factors in all classes of process, while other factors are specific to shaping, joining or surface treatment – for example:

Shaping processes: component size and geometry, accuracy and surface finish, resulting defects and properties.

Joining processes: compatibility of component shape with joint geometry and the way the process works, type of loading required on the joint, need for disassembly.

Surface treatment processes: the function of the surface treatment (corrosion, wear, aesthetics etc), whether it is possible to add a new material to the surface (from the point of view of material compatibility, and maintaining dimensions and finish).

Processing rate is not a simple characteristic of a given process, since the rate in a given situation usually depends on complex interactions between process parameters, aspects of the design, and the material being processed. For example, in welding or cutting processes, the rate depends on the type of process mechanism (mechanical, thermal etc), the component thickness, and the properties of the material being cut (thermal or mechanical). Similarly casting rates depend on the mould type, size of the casting, and the alloy being cast – all of which determine the pouring, solidification and cooling times.

(b) Annealing is used in hot and cold rolling to:

- reduce the yield stress and restore ductility, to enable further large strains to be applied
- control the microstructure (in particular the grain size, and texture – which are vital for subsequent mechanical properties and formability, e.g. for deep drawing).

Mechanisms in aluminium alloys are recovery and recrystallisation. Recovery is the rearrangement of dislocations into lower energy configurations (by annihilation, or formation of subgrains); recrystallisation is the growth of new grains of low dislocation density (and

hence low strength) from subgrains acting as nuclei (on grain boundaries, or around hard inclusions such as second phase casting particles). In annealing the processes are static (i.e. only driven by temperature), though recovery will have taken place dynamically during the deformation itself, giving an as-rolled subgrain structure.

Prior homogenization temperature and time influence the distribution of second phase particles (containing, Fe, Mn etc). This influences the extent of “particle-stimulated nucleation” (PSN) of recrystallisation (i.e. affects grain size and texture).

Deformation conditions (temperature, strain-rate, strain) also influence the recrystallised grain size and texture, as the stored energy and distribution of dislocations as sub-grains depends on these parameters. In general, lower T , higher strain-rate and higher strain promote finer grain structures (greater number of nuclei). If T is too high, or strain-rate and strain too low, recrystallisation may not take place at all.

(c) (i) Eutectoid steel (around 0.8 wt% C) has the highest hardenability in plain carbon steels, i.e. when the only diffusional phase transformations are the formation of pearlite or bainite.

As the carbon content is reduced (hypo-eutectoid steel), ferrite may form first – this occurs at higher temperatures and more rapidly during cooling, lowering the hardenability.

As the carbon content is increased (hyper-eutectoid steel), iron carbide forms rapidly on the austenite grain boundaries, again reducing hardenability. (Aside: This can partly be an artefact of conducting the austenitisation in the two-phase field (austenite + iron carbide), to avoid excessively high temperatures – hence iron carbide is already present, and there is no nucleation barrier to overcome).

(ii) Alloy additions such as Ni, Cr, Mo are deliberately made to increase hardenability. The effect is much greater than the addition of carbon. Diffusional phase transformations are retarded by the presence of the alloying elements as substitutional solutes in the iron. The solubility in austenite and ferrite differ significantly, requiring redistribution of the alloy elements. This is inherently slow, retarding the diffusional transformation and enabling martensite to form with much lower cooling rates.

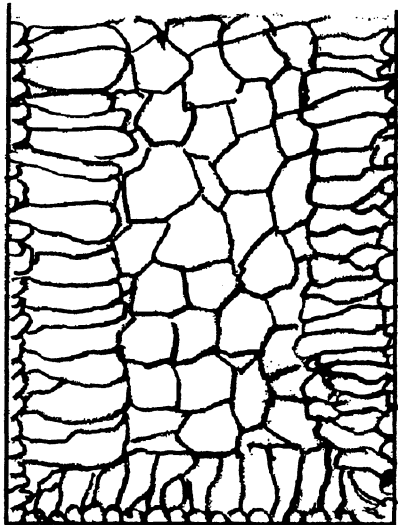
(iii) Austenitising temperature should have no influence on hardenability – there is no driving force for phase transformations until the equilibrium temperature is crossed, so it only affects the time to cool to this temperature, not the subsequent phase changes. However, excessively high austenitising temperatures may lead to grain growth, which increases the hardenability. Large grains reduce the nucleation rate for ferrite and pearlite, and also increase the distance that new ferrite/pearlite grains must grow until impingement and

completion of the transformation. Both increase the likelihood of reaching the martensite start temperature before the diffusional transformation is complete.

This question was generally not well done; many gave cursory answers to part (a) (process selection) and were not well informed on factors influencing hardenability of steels (some confusing hardenability with hardness). This question was chosen by many of the weaker candidates.

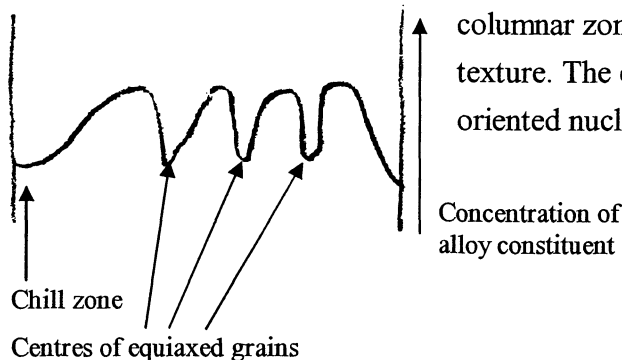
Question 2

(a)



Heterogeneous nucleation occurs on cool mould walls, with the dense array of small grains forming the **chill zone**. Favourably oriented nuclei grow out into melt (generally by dendritic growth) to form a **columnar zone**. The central part may be occupied by an **equiaxed zone**, formed by grains grown within the body of the melt.

The nuclei in the chill zone are usually randomly oriented. To form the columnar zone, competitive growth takes place, so that only those with their fast growth direction normal to the mould wall survive. The columnar zone does therefore show crystallographic texture. The equiaxed zone forms from randomly oriented nuclei, so will be isotropic.



(b) Sketch as above. The purest regions will be those which solidify first: chill zone; centres of equiaxed zone crystals. Impurity levels increase as equiaxed crystals grow out from mould walls.

(c) The relative proportions of the zones depend on their relative rates of formation; in particular, controlling the amount of equiaxed zone allows the amount of the other regions to be altered. The dimensions of the equiaxed zone depend on to what extent grains form in the

remainder of the melt. Grains in this region are still heterogeneously nucleated, but nuclei can arise from various sources, notably:

- oxide or solid metal nuclei formed on surface of melt during pouring. Increase nucleation by reducing pouring temperature. Reduce oxidation for reactive metal by using inert atmosphere.

- turbulence in melt displacing dendrite arms, which then act as independent nuclei. Increase turbulence by vibrating the mould during solidification.

- Inoculants (sometimes called Grain Refiners): Tiny quantities of specific materials (near-zero wetting angle) added just before casting to act as nuclei for the solidifying metal e.g. Add 0.05 - 0.1%TiC to Al alloys.

The columnar zone will grow until it runs into the equiaxed zone, so increasing the amount of nucleation in the body of the melt reduces the amount of columnar growth. The formation of chill zone can be prevented or reduced by heating the mould walls. If its formation is prevented completely, there will be no columnar growth and the whole ingot will have equiaxed structure.

Advantages in reducing the extent of the columnar zone:

Segregation effects (impurities pushed out by solidifying metal; may lead to embrittled zones; certainly to inhomogeneous properties).

Channels of interconnected porosity may form in between columnar grains, leading to leaky castings.

In near-net shape castings some columnar solidification may actually be desirable: the spaces between the columnar grains can form channels along which molten metal can flow (interdendritic feeding).

(d) For most applications, fine grain size is required (improved mechanical properties; effects of impurity segregation less severe; diffusion distances reduce time required for homogenising heat treatments). Grain size control easiest in equiaxed region. To a limited extent, grain size can be controlled in chill zone (cooling mould walls can increase number of nuclei, so reduce their size).

For creep-resistant applications (e.g. turbine blade), large grain-size is required. Single-crystal blade are formed by preventing the formation of any equiaxed zone, and increasing the competition between chill-zone crystals, so that (if successful) only one survives to form the rest of the casting (effectively, one columnar grain). A common device is a 'pigtail' - a helical channel through which the chill zone crystals must grow. Only a crystal with its fast growth direction along the axis of the helix will survive.

A very popular and straightforward question, generally well done.

Question 3

(a) (i) Injection mould: An automated process with polymer and fibres mixed, heated and plasticized using a screw extruder, with the molten product accumulating in a chamber. By translating the screw bodily, the contents of the chamber are then forced into the mould at high pressure and velocity. The mould is made in two (or more) parts, which are separated and the component ejected once the component is cool enough to be rigid. While the component is cooling, the next batch of polymer is accumulating in the chamber, so that the next part is made immediately.

Fibres align as a result of extension flow of the polymer (which occurs when the polymer passes through a narrow channel), and so become aligned parallel to the flow direction. Modulus and strength are enhanced in the alignment direction, the part will have variable properties within its plane. The fibre alignment will never be normal to a given thin section, so low out-of-plane modulus and strength are expected.

(ii) Hand-layup: A manual process, which may use either pre-preg sheets (fibres impregnated with uncured epoxy) or fibres woven into a fabric with epoxy added after layup. The sheets or fabric (the 'plies') are cut to shape and placed in the required locations and orientations around a former (essentially a 3D model of the required shape); several plies will be used to build up the required thickness. The curing usually requires heat, and is generally done under pressure (vacuum bagging for a complex part).

Unidirectional fibre sheets essentially show fibre strengthening only in one direction, parallel to the fibres; woven sheets show variable properties depending on the weave geometry. The orientation of the fibres within the component is optimised in the layup, and may well be variable. However, the properties normal to the plies ('secondary properties') rely simply on the epoxy because there are no fibres linking the plies, so modulus and strength are very significantly reduced in this 'out-of-plane' direction.

(b) Section variation in injection mouldings leads to a range of cooling rates. With a crystallisable polymer, thicker parts will have more time to crystallise, so will shrink more than thinner sections. This leads to distortion and internal stresses, which are particularly undesirable in a safety-critical component. Little can be done, except to try to change the design to keep sections as constant as possible. Possibly, chills could be used to accelerate cooling in thick parts (e.g. locally increase the water cooling in the mould).

Any section changes in multi-ply composites results in some out-of-plane stresses, which tend to cause decohesion and cracking between the plies. The effects are minimised by careful design to reduce stress concentrations, by making sure that the layup remains balanced, and by ensuring that the outer layers of the component are continuous (so that taper sections are achieved by cutting away sheets which will form inner sections).

(c) Injection moulding: very high set-up costs (dies are very expensive); automated, so running costs low. Good for large batch sizes (many thousands). Once the dies are made, little further change is possible.

Hand lay-up: setup costs low, but labour costs high (slow, skilled job). Good for one-offs or small runs; designs easily modified.

(d) PEEK: Thermoplastic, so can be joined by welding processes in which the polymer is heated to soften it, and the two parts are pressed together. Common processes are hot plate welding; dielectric welding. Process can be well controlled, so joint integrity can be assured. However, there will be no fibres bridging the weld, so strength relies on secondary properties. Joints should preferably be designed to be under shear or compression. Mechanical fasteners (e.g. screws) could also be used, but this introduces stress concentrations into the materials so may be undesirable. However, allows introduction of some out-of-plane strength. Adhesives are also possible.

Carbon fibre-epoxy: Not thermoplastic, so adhesives or mechanical fasteners required.

Adhesives can give good joint integrity, but surface cleanliness is vital so process is skilled.

Low out-of-plane strength (no fibres bridging joint). Constraints on geometry: preferably shear or compressive; peeling stresses must be avoided. Mechanical fasteners: enhanced out-of-plane strength valuable, but stress concentrations particularly dangerous with brittle epoxy, so screws etc should be used with care.

(e) Short fibre-reinforced thermoplastics (e.g. PEEK) are recyclable. Fibre length may be reduced still further in the process, and polymer properties may be somewhat degraded.

CFRP-epoxy (thermoset) can be recycled only to the extent of grinding it up and using it as a filler. Can also be burnt (energy recycling).

Generally sound answers, although a fair number of candidates did not appear to know that PEEK is thermoplastic.

Question 4

Steps involved in P/M process: blend metal powder (iron + graphite + alloying elements, often copper) + lubricant + binder + any other additives; fill die and compress cold in uniaxial press to form 'green' compact; (optional machining in green state); sinter by heating to burn off binder, then allow interdiffusion to bond particles and reduce porosity. May need small amount of machining to finish. Heat treatment may also be possible and can be combined with quenching from sintering furnace.

Advantages of P/M route over machining from bar stock: near-net shape process so much less waste of material, lower machining costs; low energy requirements; can make alloys which would be difficult to machine; more homogeneous distribution of alloying elements.

Maximum size of component is limited by press size – typical components are up to a few hundred grams mass.

Final density depends on: initial density of compact before sintering, which in turn depends on particle shape, particle size distribution, compaction pressure, effectiveness of lubrication and design of die; sintering time; sintering temperature.

Other processes which can be used to achieve higher density: HIPing; sinter forging; liquid metal infiltration.

Smaller particles sinter faster because of two factors: the smaller particles have a greater surface area per unit volume and the reduction in surface energy therefore provides a greater driving force for sintering; and the smaller particles lead to shorter diffusion paths for atoms which need to move to close pores, and thus to more rapid reduction of pore size.

The equation suggests that for any finite particle size a , there will always be a non-zero rate of increase in density. In fact, the density cannot exceed the value for the solid metal, and so the equation cannot remain valid when the porosity reaches zero.

$$\frac{d\rho}{dt} = \frac{A}{a^3} D_0 \exp(-Q/\bar{R}T)$$

We know that sintering for time t_1 at temperature T_1 leads to the same density as sintering for t_2 at temperature T_2 . The starting conditions are the same. If we assume that the change in particle size a during the process is small, so that in each case $d\rho/dt$ is constant during sintering, then:

$$t_1 \exp(-Q/\bar{R}T_1) = t_2 \exp(-Q/\bar{R}T_2)$$

Take logs:

$$\ln\left(\frac{t_2}{t_1}\right) = \frac{Q}{\bar{R}}\left(\frac{1}{T_2} - \frac{1}{T_1}\right)$$

Substitute for data from question, $R = 8.31 \text{ J mol}^{-1} \text{ K}^{-1}$ (databook):

$$\ln\left(\frac{45}{30}\right) = \frac{Q}{8.31} \left(\frac{1}{(1175 + 273)} - \frac{1}{(1200 + 273)} \right)$$

Hence $Q = 287.5 \text{ kJ mol}^{-1}$

The 'bookwork' section was well done, although candidates showed little knowledge about machining from bar. Disappointingly few candidates were able to rearrange the equation $t_1 \exp(-Q/RT_1) = t_2 \exp(-Q/RT_2)$ to produce an explicit expression for Q , and even fewer could then substitute numbers and get the correct numerical result.