

## Engineering Part IIA Module 3C1 / MET1 Paper P4A

### Materials Processing and Design

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1. (a) Properties required: High strength and modulus along the fibre length. Achieved by aligning the molecules. This will be done in two ways:

The HDPE will be extruded through a die; there will be some extension flow during this process.

Once the HDPE comes out of the die, it should be drawn down. This will result in further extension and molecular alignment.

(b) The beam needs to have a high elastic modulus along its length. This means that a high volume fraction of continuous carbon fibres is needed, and they should be accurately aligned. The obvious route is pultrusion: fibres are passed through resin bath, the required shape is produced by drawing through a die, and the beam section cured in a continuous production line process.

(c) The wall thickness of the bottles must be as small as possible to reduce the amount of material consumed, so high strength is required. The bottles are stretch-blow moulded to achieve biaxial alignment of the molecules. Parisons (injection moulded pre-forms, incorporating a screw thread) are stretched along their length giving longitudinal alignment, and then blown into a closed cavity to align the molecules in the hoop direction.

(d) Metal Injection Moulding: high-strength part produced in high volumes, thin section, good surface finish required.

- Stainless steel, very fine powder (about 5  $\mu\text{m}$ ): 60% gas atomised powder + 40% water atomised powder + binder (combining green/brown strength with good powder flow properties) is injection moulded (as for polymers) in a mould 30-50% bigger than the final artifact
- Debinding in a highly controlled furnace (this stage is very critical, and can take many hours, although quicker processes are being developed)
- 'Brown' compact sintered at 1300  $^{\circ}\text{C}$  in a vacuum furnace, giving a compact with density typically 85-99% (in this particular case, 99.4%) and dimensional accuracy of 0.5-1%
- The final product is polished (which can only be done if the porosity is very low).

### Advantages of MIM:

- low die wear rates; complex shapes (variations in wall thickness, moulded-in decoration) with high dimensional tolerances can be made; low and uniformly distributed porosity means products take high surface polish and have excellent mechanical properties. Particularly useful for high-volume production.

(e) The part must contain interconnected porosity, so must not be fully dense. Made by cold-pressing bronze powder into a mould, and then sintering ( $\geq 0.7T_M$ ) until sufficient mechanical strength is achieved.

*Extract from examiner's report:*

*A popular question which should have been straightforward, drawing as it did on examples taken directly from lecture notes.*

*(a) Most recognised that chain alignment was needed for high modulus and strength. However, there was confusion between chain alignment and melt swell. To maintain alignment, post-extrusion draw-down is required. Using a long die land does the wrong thing: it allows molecules to coil up before leaving the die, so reducing melt swell but at the cost of reducing chain alignment.*

*(e) Several people did not know what an oil-filled bearing was, although it had been described explicitly in lectures.*

2. (a) Example 1: Recrystallisation of non-heat treatable aluminium alloys after hot rolling: second-phase particles act as nuclei for recrystallisation (particle-stimulated nucleation, PSN). Hence the particle density resulting from homogenisation will influence the recrystallised grain size. More importantly in this context, the texture is affected, since PSN generates random texture, while grain boundary nuclei inherit the texture of the deformed state. The main property effect is therefore the subsequent anisotropy in yielding behaviour (and thus susceptibility to earing in can-making, for example).

Example 2: Quench sensitivity in heat-treatable aluminium alloys: in extrusion, the solution heat treatment occurs in the press itself, with the product being quenched as it emerges. During cooling it is desirable to retain a supersaturated solid solution, but precipitation of coarse non-hardening phases may occur on dispersoids – the tendency to do this is called quench sensitivity. The allowable severity of the quench is limited by heat conduction and the need to avoid distortion of the extrusion. The consequence is the reduction in peak strength after subsequent age hardening, as some of the solute is not available to form fine hardening phases.

(b) (i) Successful mould filling in casting: the key physical behaviour is that liquid metal retains fluidity and reaches and fills all the mould features before solidification closes off the supply of incoming metal. This is governed by the cooling history, which depends on the following characteristics:

*process:*

mould type (and thus thermal properties) – controls rate of heat extraction from the component;

pour temperature – influences time for liquid metal to reach solidification temperature;

process type (gravity or pressure casting).

*material:*

alloy thermal properties – influences rate of heat extraction;

alloy viscosity – influences ability to flow into mould features;

alloy solidification behaviour (solidus and liquidus temperature as function of composition, from phase diagram) – controls loss of viscosity after onset of solidification, and freezing range.

*design:*

component shape and size – influences rate of heat extraction (surface area to volume ratio, both for casting as a whole, and for cooling around local features). Aspect ratio of narrow features is particularly limiting. Possibility of chills to alter heat flow.

mould, numbers and locations of feeders, risers – ensuring filling of mould without turbulence; supplying reservoirs of molten metal to avoid macroporosity; minimising effect of section changes

(ii) Avoidance of embrittlement in welding of low alloy steels: the key physical behaviour is the phases formed on decomposition of austenite, in the heat-affected zone and weld metal, in particular avoiding the formation of martensite. This is governed by the cooling history, and the hardenability of the alloys – hence determined by:

*process:*

welding process used, and process parameters such as power, speed (i.e. heat input) – govern the thermal history (peak temperatures and cooling rates); e.g. arc processes generally slower cooling than keyhole processes.

preheat, post-weld heat treatment – preheat reduces the cooling rate; PWHT aims to temper any martensite formed.

*material:*

alloy thermal properties – influences thermal history;

alloy hardenability – determines microstructural response of alloy as a function of cooling rate (CCT diagrams, which as a very important omission don't take account of

grain size): higher hardenability implies greater susceptibility to forming martensite and hence embrittlement.

*design:*

joint geometry and material thickness – influences thermal history.

(c) (i) Laser hardening: component tolerance and finish critical, and often very small - lasers give minimal distortion and no change in surface finish, and can be tuned to small areas including the internal surfaces of a bearing.

Thermal spraying: deposits a surface layer, so component tolerance and finish is lost; difficult to control on small-scale and for internal surfaces; porous deposit not as effective for high contact stresses.

(ii) Spot welding: ideal low-cost process for thin steel sheet, with non-continuous join needed (for internal seams – not suitable for the edges).

Epoxy resin: slower process to conduct in this geometry, with fume hazards; susceptible to degradation in hot water.

*Extract from examiner's report:*

*A descriptive question which could be answered appropriately in a number of styles; unstructured waffle, however, gained few marks. Answers ranged from annotated diagrams, through bullets to pure essay-style. Generally (but not exclusively), the essays contained the lowest amount of relevant information.*

*(a) There was some confusion between dispersoids and the precipitates which are subsequently produced during age-hardening. Many people made only slight reference (or none) to their influence on properties.*

3. (a) *Hardenability* is a measure of ease of forming martensite when quenching steel from austenite.. A steel with a high hardenability is one which has a low critical cooling rate, so that even slow cooling will lead to a martensitic structure. The higher the hardenability, the larger is the component which can be hardened in depth on quenching.

The Jominy end quench test involves heating a standard cylindrical specimen to an austenitising temperature and quenching from one end with a controlled water jet. After quenching, hardness measurements are made at intervals along its length. The hardness variation along the specimen is a result of microstructural variation which arises since the cooling rate decreases with distance from the quenched end.

The Jominy end-quench test is used to measure the hardenability of a steel.

(b) The *equivalent diameter* of a component is the diameter of an infinitely long cylinder which, if subjected to the same cooling conditions as the component, would have a cooling rate on its axis equal to that at the position of slowest cooling in the component.

From Figure 1, it can be seen that the limiting value for  $f$  corresponds to  $y/z = 0$ , i.e. long cylinder and  $x/y = 0$ , i.e. solid cylinder. For a long solid cylinder, the equivalent diameter is equal to twice the cylinder radius. Hence  $f$  is equal to 2, as  $y$  equals the radius.

(c) The critical cooling rate is approximately  $7000^\circ\text{C}/\text{min}$ . Quench cracking may arise if high thermal gradients are experienced on cooling, exacerbated by the brittleness of the martensite. This can be overcome by quenching the steel into a molten salt bath to a temperature just above the martensite start temperature ( $M_s$ ) and allowing the steel to equilibrate at that temperature. Then cool slowly in air to form martensite. This avoids thermal contraction stresses between surface and interior. This is martempering.

(d) 340 HV at centre for water quench and  $400^\circ\text{C}$  temper for 1 hour, bar diameter = 50 mm. The microstructure at the centre is 7% ferrite, 83% bainite, 10% martensite (approximate values).

(e) From dimensions given,  $x = 70$  mm,  $y = 13$  mm and  $z = 200$  mm. Thus  $y/z = 13/200 = 0.065$ , and  $x/y = 70/13 = 5.38$ . Using the equivalent diameter curves in Figure 1, it can be found that

$$f = 1.5, D_e = f \cdot y = 1.5 \cdot 13 = 19.5 \text{ mm}$$

Using the CCT diagram for 0.5% Ni-Cr-Mo steel in Figure 2, the microstructure in the centre (position of slowest cooling) of a 19.5 mm diameter bar quenched in water is approximately 10% bainite, 90% martensite. The hardness at its centre is 570 HV.

From the CCT diagram, it can be found that the diameter of a bar which may be quenched in oil to give the same microstructure is about 14 mm. Because the factor  $f$  is 1.5 for both water and oil quenches (see Fig.1), the ratio of the equivalent diameters ( $14/19.5 \sim 0.7$ ) will give the scale up on all dimensions. Thus:

External diameter:  $0.7 \times 96 \text{ mm} = 67.2 \text{ mm}$

Internal diameter:  $0.7 \times 70 \text{ mm} = 49 \text{ mm}$

Length:  $0.7 \times 200 \text{ mm} = 140 \text{ mm}$

*Extract from examiner's report:*

*A straightforward question, generally well done.*

4. Nucleation is expected to be exclusively heterogeneous for ingots. It may occur on mould walls, producing a chill zone comprising many small crystals. These grow competitively out into the melt, resulting in a relatively small number of columnar grains which have their fast growth directions normal to the mould walls. Growth ceases when they run into either crystals growing from the opposite mould walls, or run into crystals (equiaxed) which have grown within the melt. The equiaxed crystals nucleate by a range of mechanisms: surface nucleation as the molten metal flows into the mould; growth on 'inoculants' added to promote heterogeneous nucleation; growth of dendrite arms which have been displaced by the turbulence of the melt.

All crystals push impurities out into the melt ahead of the solidification interface. If the cast structure is fully columnar, the centre line (where the columnar grains meet) may have very high levels of impurity, and suffer weakness.

(i) A single-crystal fan blade is made by investment casting, and the mechanism for ensuring that only one crystal grows into the cavity is built into the mould design. Chill zone crystals nucleate on the cold mould wall at one end of the cavity, and the heat flow is engineered so that they grow into the turbine blade cavity by directional solidification. The crystals are forced to grow through a 'pigtail' (a helical channel). This causes very fierce competition between grains, and normally only the most favourably oriented grain will survive to grow into the rest of the casting cavity.

(ii) An ingot which is to be hot-rolled must contain neither macroporosity nor a centre line of weakness. One way of avoiding macroporosity in steel ingots is by balanced evolution of gas during solidification. The centre line of weakness is avoided by preventing fully columnar structures from forming: ensure some equiaxed zone forms. Continuous casting (the normal precursor for mass-market steel for hot-rolling) produces equiaxed crystals in the centre of the ingot, surrounded by columnar crystals.

(iii) Uniform grain size and shape implies that the structure is fully equiaxed, with no columnar zone and no chill zone. Extensive nucleation in the melt is required, and will probably be achieved by pouring close to the melting temperature so that there is a lot of surface nucleation (as well as perhaps some of the other mechanisms described above).

(b) The statue is clearly a net-shape casting, so cannot be cold-deformed. Homogenisation will have to rely on heating ( $\geq 0.7T_M$ ) to allow diffusion to even out concentration gradients. In order for the heating time to be kept as short as possible, diffusion distances must be minimised. Since the concentration needs to equilibrate between edges and centres of grains, columnar growth should be avoided, and the

equiaxed grain size must be minimised. This is achieved by maximising the number of nuclei in the melt: pour close to the melting temperature; add inoculants; vibrate the mould to encourage dendrite arms to float off and act as nuclei. The higher the homogenisation temperature the quicker the treatment; the top of the single-phase region is at 900°C. The question doesn't ask about porosity, so no need for HIPing.

If the cast material can be cold-deformed and recrystallised, less care is required in casting it. The homogenisation can be achieved very rapidly and in a controlled way (also allowing the grain size to be modified). As the recrystallisation interfaces sweep through the deformed material, the chemical composition is evened out.

(c) (i) Al-2%Si is well off-eutectic and so has a large semi-solid range. Liquids have a large coefficient of thermal contraction, so this alloy will suffer considerable shrinkage during solidification. There will also be gas coming out of solution as the metal solidifies. Porosity forms between dendrite arms.

The 12% Si alloy is eutectic, so has no semi-solid range, and the liquid shrinkage is not a problem. Gas will still come out of solution, but the total amount of porosity will be much lower.

The alloy could be vacuum-degassed to remove the gases in solution before casting, but this will not prevent the shrinkage-induced porosity. This may be removed by HIPing (hot isostatic pressing) of the solid casting, which closes internal cavities and forces the gas out. The alloy could be deformed (e.g. rolling) to squeeze out the porosity, but the brittle Si precipitates may result in some cracking if this is done.

(ii) During eutectic solidification, Si forms brittle needles in the Al matrix. Adding 0.2% sodium poisons the ledge growth mechanism in the Si semi-metal, and forces the crystals to form more rounded shapes. The crystal size is also reduced. The effective critical crack length is reduced, and the alloy toughness increased. Increasing the alloy cooling rate will also reduce the precipitate size.

*Extract from examiner's report:*

*For a question explicitly about casting and post-casting treatments, it was surprising to find some answers focusing on quite different shaping processes (for rather few marks). People frequently lost marks by failing to explain their reasoning.*

*(a) (ii) Many people had no idea what was wanted here (avoidance of macroporosity and of centre-line segregation), and wrote instead about texture and minimising forces by grain size control.*

*(b) Astonishing numbers of people started their answers by correctly noting that this statue was a net-shape casting, and then went on to advocate deforming and annealing it.*

*(c) Generally weak answers for both parts.*

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