

**MET Part I Paper P4A: 2003**  
**Part IIA Module 3C1: 2003**  
**Answers**

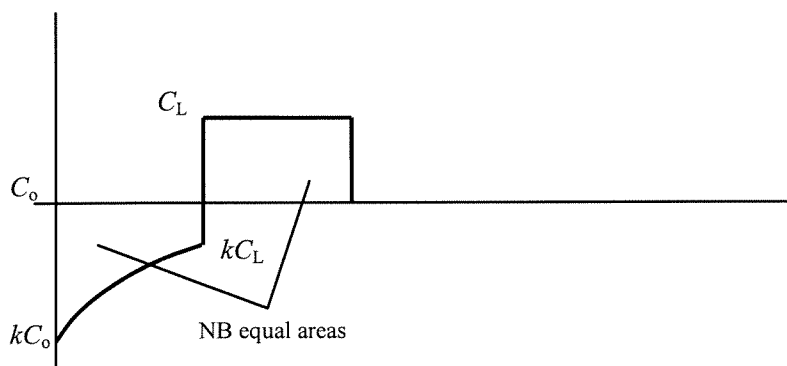
**Q.1**

(a) Two methods are as follows. (i) cast using inoculant to achieve small initial grain size and low inhomogeneity due to segregation. Homogenise by heat treatment at sufficient temperature and for long enough to achieve adequate diffusion distances. (ii) cast taking no special precautions, accepting significant segregation and large grain size. Then mechanically work e.g. by rolling, extrusion etc. followed by heat treatment to allow recrystallisation, homogenisation and grain growth. Higher degree of cold work will favour finer grain size as produces greater driving force for nucleation of new grains. May need more than one stage to achieve adequate uniformity and fine grain size. (ii) involves extra thermomechanical treatment compared with (i) so will be more expensive.

(b) (i) Zone refining is used to refine semiconductor materials such as silicon, in which very high degrees of purity are required. The process involves taking a long bar of solid, melting a small length at one end using a small moving furnace, and traversing this molten zone gradually through the length of the bar. The solid which is deposited at the end of the bar is purer than the liquid (it will have composition  $kC_0$ ), and the liquid picks up impurity and carries it along the bar. After a short 'initial transient' zone, steady state is reached: the concentration of impurity in the liquid reaches  $C_0/k$ , so the solid deposited by the liquid has composition  $C_0$ . No further purification takes place on that pass. When the furnace passes along the furnace on its next pass (or the next furnace: to speed up the process several furnaces will run along the bar one-after-the-other), the composition of the first solid to be re-precipitated is approximately  $k^2C_0$ . Subsequent passes along the bar by the furnace will carry further impurity along in the liquid region, gradually generating a region of high purity at the end of the bar where the furnace starts its traverse. The concentration of impurity tends to zero at one end of the bar; all the impurity is swept to the other end. The 'dirty' end of the bar may finally be cut off, and the impurity concentration evened out by sweeping the furnace back in the reverse direction.

(ii)

Sketch of composition:



Move molten zone of width  $L$  a distance  $\delta L$  from  $x$  to  $x + \delta x$ , area  $A$ .

Balance impurity contents in region melted, resulting liquid, and solidified region

$$\delta x C_o A - \delta x k C_L A = L \delta C_L A$$

$$\therefore \frac{L \delta C_L}{C_o - k C_L} = \delta x$$

$$\text{Integrate: } -\frac{L}{k} \ln(C_o - k C_L) = x + \text{const}$$

Boundary conditions:  $x = 0, C_L = C_o$

$$-\frac{L}{k} \ln\left(\frac{C_o - k C_L}{C_o - k C_o}\right) = x$$

Rearrange and substitute  $C_s = k C_L$

$$C_s = C_o \left\{ 1 - (1 - k) \exp\left(\frac{-kx}{L}\right) \right\}$$

## Q.2

(a) MIM: Mix metal powder with high volume fraction (up to 50%) binder and additives. Binder is polymeric, with a waxy consistency: typically a metal stearate. Injection mould, as for polymer injection moulding, into a die which is 30-50% bigger than the required final dimensions of the product. In a stage known as debinding, polymer is removed from the injection moulded part by heating. This is a critical stage, and needs to be done very carefully (and often slowly) to remove binder without introducing distortion. The 'brown' compact is then sintered at high temperature (typically 1300°C), normally in a vacuum furnace to prevent oxidation of the powder. The product has low porosity (can be as low as 0.5%), and dimensional accuracy of 0.5-1%. The low porosity allows the product to be polished.

MIM is particularly suited to this application because:

- high dimensional accuracy in a small and intricate part;
- low porosity so parts can be polished;
- low% and uniform distribution of porosity gives excellent mechanical properties;
- economical: low material wastage; low die wear rates so die lifetime is extended;
- particularly good for high-volume production.

(b) The internal screw thread means that it will not be possible to use a rigid die to compact the powder. Possible routes would be:

1. Hot isostatically press. Powder canned in thin sheet-metal container. May contain sintering aid (e.g. 0.5-1%MgO to form low-melting-point glass). Heated (about 1600°C) under high isostatic pressure (about 10MPa).

Advantages: fast; good mechanical properties (low porosity, low grain growth).

Disadvantages: low dimensional accuracy; equipment is expensive.

2. Isostatically press and then sinter. Alumina powder plus 4% aluminosilicate binder plus 0.5% MgO as sintering aid) placed in rubber mould and compressed isostatically, using hydraulic fluid at about 30MPa. The green compact is removed from the rubber mould and sintered at (about) 1600°C for 1h.

Advantages: cheaper than HIP; dimensional accuracy can be improved by machining green compact.

Disadvantages: Dimensional accuracy low unless machined; mechanical properties lower than for HIP.

(c) (i) Bathtubs. Properties required: cheap; reasonably high elastic modulus (not too much flexibility); robust (reasonably high toughness, good scratch resistance); can be made in different colours.

Mechanical properties indicate that a thermoset polymer will be needed for optimal properties. A composite will have improved strength and elastic modulus over the polymer on its own.

Use spray lay-up, with chopped glass fibre and polyester resin. These are mixed together in a hand-held gun and sprayed onto a mould.

This is the cheapest composite fabrication route, ideal for this application, and uses a thermoset matrix which has good rigidity. Low skill required, and minimum of equipment (gun; re-usable mould; ventilated workspace because of styrene hazard).

Disadvantages are: composite is resin-rich; very limited range of mechanical properties, and relatively low strength. However, mechanical properties will be good enough for this relatively undemanding application.

Vacuum moulding of pigmented PMMA sheet (thermoplastic) into female mould also used for cheap solution.

(ii) Bottles. Properties required: impermeable to CO<sub>2</sub>; cheap, so use thinnest walls possible, so require highest possible strength and toughness from the material.

Polymer: PET has low CO<sub>2</sub> permeability; bottles also have a coating of 4µm of PVDC to improve storage properties.

Manufacture: Stretch blow moulding. A preform is made by inflating an extruded tube of polymer into a mould. Preform removed from this mould, reheated and stretched along its length (causing chain alignment in the longitudinal direction) before being inflated into another mould (causing alignment of polymer chains in the hoop direction). This biaxial alignment increases polymer strength, so thinner walls are required.

An alternative process would be blow moulding without the stretch stage, but alignment of chains only in the hoop direction means that strength is lower and walls must be thicker.

(iii) Carrier bags. Properties required: cheap, high strength, high toughness.

Polymer: Can be LDPE (lower strength so bags must be thicker and so more expensive, but this makes them tougher); cheaper (thinner) bags are made from HDPE or PP (tend to split and tear).

Manufacture: Film blowing. Inflate a tube of polymer (extruded through annular die) to form a large bubble. Biaxial alignment achieved by inflation (hoop direction) and tensioning from windup rolls. Bags formed by cutting and heat-sealing the film.

### Q. 3

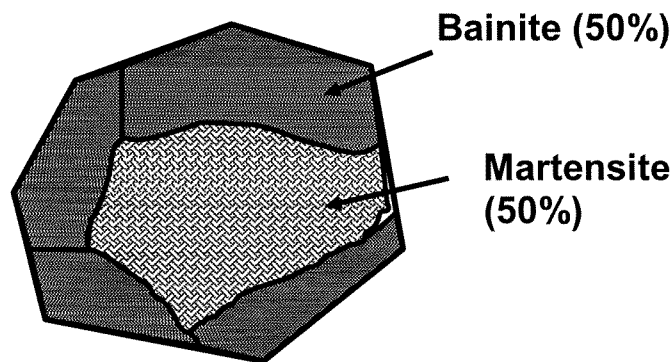
(a) Equivalent diameter of a component is the diameter of a long solid cylindrical bar which has the same cooling rate at its centre as the position of slowest cooling in the real component, when quenched in the same medium.

(i) For small  $y/z$ , the tube is effectively very long. Cooling at the position of slowest cooling (halfway along the tube, somewhere near mid-thickness of the tube wall) is unaffected by heat transfer at the end of the bar – heat flow is essentially radial to the inside and outside of the tube, so independent of  $z$  (and hence  $y/z$ ).

(ii) The limiting value of  $f$  indicated corresponds to  $x/y = 0$  (i.e. solid cylinder) and  $y/z = 0$ , (i.e. long cylinder). In this limit, the component is already a long solid cylinder, and so the equivalent diameter is equal to the actual diameter. From the definition of  $D_e$ ,  $f_{lim}$  must equal 2 (as  $y$  then equals the radius).

(b) The critical diameter  $D_0$  is the diameter of a long solid cylinder which will form 50% martensite at the centre of the bar on quenching.

Microstructure:



For the  $\frac{1}{2}$  NiCrMo steel:

Air cool:  $D_0 = 1$  mm

Oil quench:  $D_0 = 22$  mm

Water quench:  $D_0 = 32$  mm

(c) For centre hardness of 300–320:

Air cooling cannot achieve required hardness.

Use oil quenching and temper for 1 hour at 400 °C, or water quenching and temper for 1 hour at 500 °C.

These heat treatments provide surface hardness of 400 and 350 HV respectively, so neither is able to meet the specification – hence require a separate surface treatment. Laser transformation hardening will produce 100% martensite in a thin surface layer,

which in this steel is expected to have a hardness of 600 HV, which is too high. Hence an alternative treatment is required.

One option is to carburise before the quenching/tempering treatment, such that the quenched/tempered surface hardness is raised to the target range. Nitriding could also be used provided the resulting hardness is correct; Cr and Mo both readily form nitrides. This is a good choice since it can be done at the tempering temperature, so surface and bulk properties are produced in one process step.

#### Q. 4

(a) There is a limited reduction possible per stand, and until the strip is about 3mm it cannot be coiled up. Hence it is most efficient to run several deformations one after the other to a thickness which can be coiled, to avoid the use of very long run-out tables, or very limited metal volumes per rolling set-up.

Rolling load and torque governed by:

- material yield stress (function of temperature and strain-rate)
- friction
- reduction per pass
- roll radius (smaller the better, so small work rolls are backed by bigger rolls

to provide stiffness)

Main control issues:

- balancing load/torque per stand (i.e. power consumption)
- control of gauge (thickness), flatness and surface finish
- control of speed: continuity of metal flow means roll speeds must be matched from stand to stand (to avoid the strip being stretched to much, or worse going into compression and buckling)
- control of temperature: vital for obtaining desired deformation microstructure and recrystallisation after rolling (on the coil)

Anisotropy means different yield properties in different directions (notably parallel and perpendicular to the rolling direction). Texture means the non-random orientation of the lattice in the deformed and recrystallised grains, which is a major cause of anisotropic yielding. It is significant in subsequent cold forming operations with the sheet (stamping, deep drawing etc) when the sheet may wrinkle and deform inhomogeneously – e.g. causes earing in drawing of cans which may lead to higher scrap rates.

(b) Dominant factors:

- function of the treatment (wear, corrosion, appearance, fatigue resistance etc)
- compatibility of the process with the material substrate
- compatibility/adherence of any coating required with the material substrate

Wear resistance is not specific to a given surface engineering process, but depends on complex combinations of parameters: the material which is surface treated, the material against which wearing takes place, the loading applied to the contacting surfaces, the properties of the treated surface (hardness, microstructure, defects etc) which in turn depend on the surface treatment processing conditions, and the environment and temperature in service.

(c) Grain refining takes place in the part of the heat-affected zone which goes into the lower part of the austenite field ( $T_p$  of order 900-1000°C). The original ferrite/pearlite grains transform to austenite, with several austenite grains per original grain. The temperatures are too low and the times too short for any grain growth, so on cooling the transformation reverses, with several ferrite/pearlite grains nucleated per austenite grain, refining the grain size.

In the HAZ adjacent to the weld metal, the peak temperature is much higher ( $T_p$  of order 1200°C). Austenite grains form very rapidly and can grow at these temperatures in the timescale of welding. With a modest cooling rate, ferrite and pearlite re-form, but the grain growth as austenite dominates, giving a net increase in grain size. Faster cooling rates give a risk of martensite formation, since the larger grains cause higher hardenability. Hence embrittlement of the weld may result.