

(i)  $A_{c3}$  is the equilibrium temperature at which austenite transforms to ferrite, the  $\gamma / \gamma + \alpha$  boundary.

$A_{c1}$  is the equilibrium temperature of the eutectoid reaction for the steel.

$M_s$  and  $M_f$  refer to the temperatures at which martensite starts and finishes forming from austenite.

Alloying delays ferrite/pearlite formation (kinetic effect). The alloying additions are substitutional and so their diffusion rates in steel are slower than interstitial C. Their presence will slow down reconstructive phase transformations (in which elements partition by diffusion in the transforming austenite) from austenite to ferrite and pearlite. This slows down the onset of the transformation from austenite, shifting the CCT curves to the right, enabling martensite to form with lower cooling rates hence increasing hardenability.

(ii) The critical cooling rate is (approximately – by extrapolation) 3000°C/min.

(iii) Critical diameters (50% martensite, 50% bainite): Air 2.0-3.5 mm, Oil 45-50 mm, Water 55-60 mm.

(iv) 50 mm bar: Microstructure at centre 55% bainite, 45% martensite, hardness 400 HV.

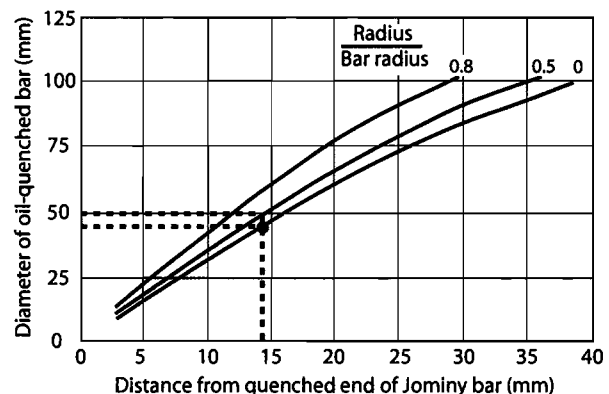
250 mm bar: Microstructure at centre 10% ferrite, 60% pearlite and 30% bainite, hardness 280 HV.

The question asks for the hardness gradient, and because the curves are very non-linear it is necessary to define the hardness at three points (typically centre, surface and half-way to surface). The hardness at the centre of a 50 mm bar (quenched in oil) after tempering at 500°C for 1 hour is 340 HV. The surface hardness corresponds to a zero radius bar, so 400HV. For halfway to the surface, using the curve “radius/bar radius=0.5” (Figure 2), for a 50 mm bar this position corresponds to a distance of 14 mm from the end of a Jominy bar. At this distance, using the curve “radius/bar radius=0”, it can be found that a 44 mm diameter bar has the same cooling conditions at its centre (see Figure below). Hence the halfway position in a 50 mm bar diameter corresponds to the centre of a 44 mm bar. For a 44 mm bar, the hardness at the centre is 360 HV.

**Centre: 340HV**

**Half way to edge: 360HV**

**Surface: 400HV**



Microstructural and mechanical property changes in tempering: Martensite is very hard and very brittle: the lattice contains a supersaturated solid solution of carbon atoms

which result in a high elastic strain in the martensite, so impeding dislocation movement. On tempering, hard precipitates of cementite ( $\text{Fe}_3\text{C}$ ) or alloy carbide form in a very fine dispersion (small, closely-spaced particles). The matrix reverts to ferrite in fully tempered steel. The steel loses hardness but gains the ability for dislocation movement (plastic deformation), so gains toughness. The distribution of carbide particles mean that dislocations still cannot move easily, so a high yield strength is retained.

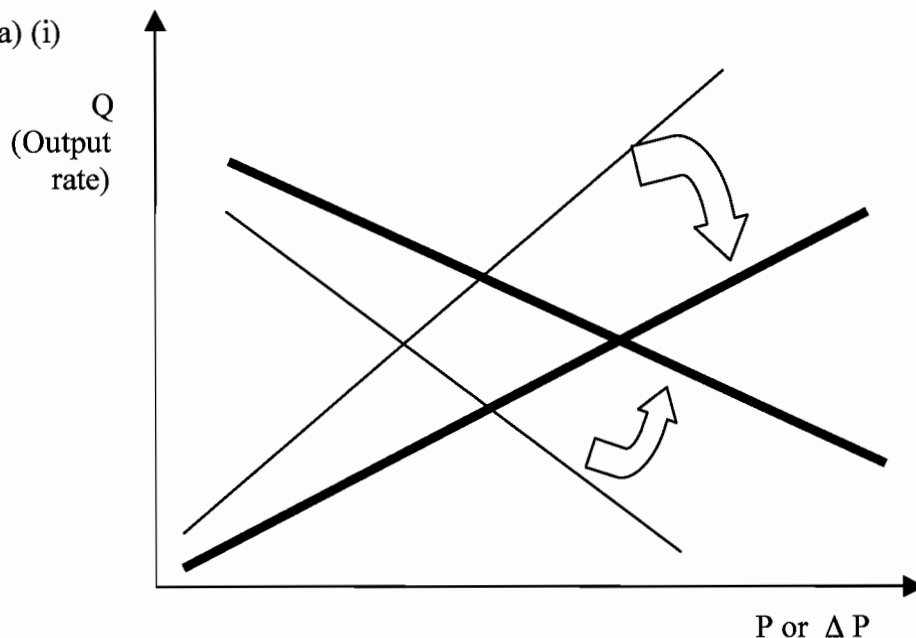
(b) (i) Knives need to retain a sharp edge, so hardness and strength critical. Martensitic stainless steel: characterised by high hardness and strength. Low toughness of martensite is a disadvantage, so some tempering is commonly done to create a compromise between attributes.

(ii) Austenitic stainless steel: very good toughness at low temperatures. Ferritic and martensitic stainless steels exhibit a toughness transition from tough to brittle behaviour at low temperatures.

*Examiner's comments: The parts which required data to be read from steels and cooling diagrams were straightforward (although it was necessary to extrapolate), and generally well done. Parts of the question which required greater understanding of the material were less impressive, and explanations about microstructural changes were particularly badly done.*

2.

(a) (i)



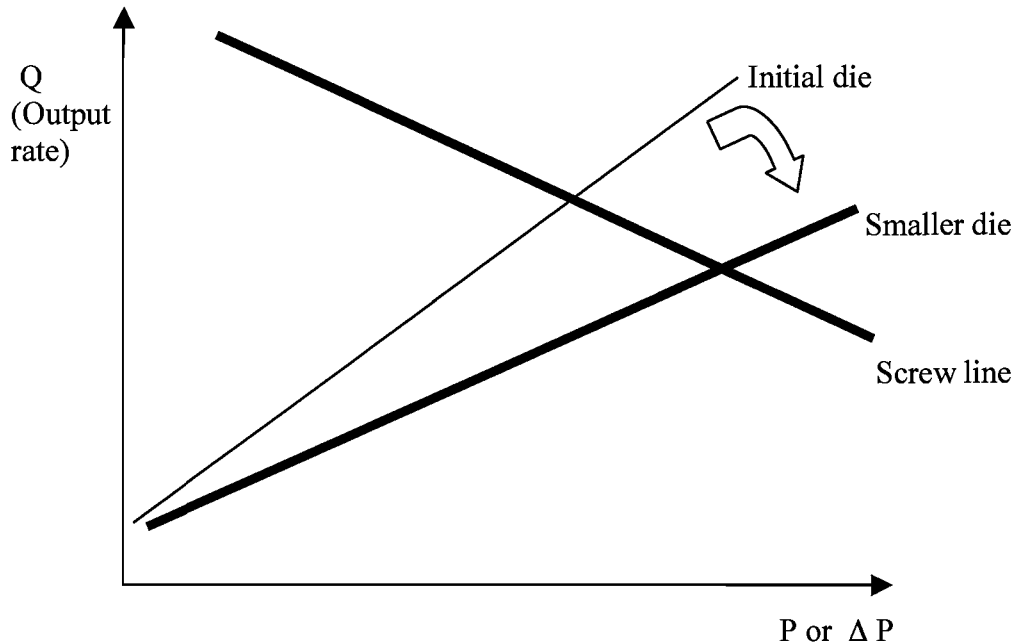
Adding glass fibres increases the viscosity of the extrudate.

Effect on screw line ( $Q = A\omega - B \Delta P/\eta$ ): Decreases the amount of back-flow, so the gradient of the screw lines becomes less negative. The amount of drag-flow is unchanged as this is independent of viscosity. Net result is that the rate which the screw moves polymer along the barrel is increased. Effect on die line ( $Q = C P/\eta$ ): Polymer less more easily out of the die.

Other factors not shown on diagram: leakage past flights of screw.

Effect on operating point: pressure increases, but output rate is little affected because of the counterbalancing effects of the two flow equations. Whether it rises or falls slightly depends on relative magnitudes of constants B and C.

(ii) Reducing die diameter reduces the flow rate out of the die, increasing the pressure.



(b) Problems with extruding HDPE are:

Differential shrinkage in sections of different thickness, because of differences in cooling rate causing variations in crystallinity;

Melt swell, causing distortions and dimensional variations. All effects will vary with polymer chain length, branching etc, so may vary from batch to batch. Try to keep composition of polymer constant.

(i) Corners of section have increased thicknesses, so will shrink more, and the square section will distort. There will also be melt swell effects. Use a die which is designed to produce the correct output. Better: redesign section to have uniform wall thickness (no sharp corners). Helical chain distribution from extrusion may cause corkscrewing of the section: use a breaker plate to straighten chains.

(ii) Melt swell effects. Dimensions will depend critically on amount of crystallinity, so important to keep cooling rates constant. Distortion may arise from different alignment in different parts of the section. For all of these, melt swell can be reduced by: rapid cooling of extrudate; use of long die land. Post-extrusion drawing can improve dimensional tolerances.

Die wear must also be monitored.

(c) Extension flow, resulting in alignment of polymer chains parallel to extrusion direction, occurs as polymer is extruded through a die. Polymer will have enhanced elastic modulus and strength in the extrusion direction.

(i) Maximise anisotropy by post-extrusion draw-down (as in cold-drawing).

(ii) Allow chains to coil up by keeping polymer hot after passing through die. This can be done best by using a long die land, which will retain the dimensions of the extrudate.

*Examiner's comments: An awful lot of muddle in manipulating lines on the diagrams!*

## 3. (a)

## (i) A: MIM:

- Uses conventional polymer injection moulding technology with a polymer-metal feedstock to produce the initial green compacts. Produces closely-toleranced parts containing uniform particle distributions.
- Very fine powder (about 5  $\mu\text{m}$ ): 60% gas atomised powder + 40% water atomised powder + binder is injection moulded (as for polymers) in a mould 30-50% bigger than the final artefact
- 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 600 °C in a vacuum furnace, giving a compact with density typically 85-99% and dimensional accuracy of 0.5–1%

## 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.
- Typically used for small thin-section complex parts produced in high volumes e.g. small gears, disc drive parts, camera parts, surgical instruments, spectacle frames and luxury goods. For some metals it competes with investment casting (lost-wax casting):

B: Pressure die casting: Metal injected at high pressure into permanent metal mould. Turbulence problematic so mechanical properties compromised, but process is fast, repeatable and cheap.

C: Injection moulding: polymer injected at high pressure into water-cooled mould. Process is fast, repeatable and cheap; mechanical properties are good.

## (ii) Need to consider:

Mechanical property requirements; environmental requirements (e.g. temperature, chemicals); dimensional tolerances.

Manufacturing costs: Materials (wastage), labour costs, equipment costs.

MIM is a more expensive process than the other two, and less highly automated, so likely to be avoided for higher volume applications.

## (b) (b) Cold working vs hot working:

Advantages: better tolerance and surface finish; scope for simultaneous strengthening by work hardening; modest formability in tension without necking at low strain.

Disadvantages: higher loads needed; lower capacity for large strain deformation in single operation; can lead to marked texture and anisotropy of properties.

Hot forming typically 0.5 – 0.95  $T_m$  (in K). From Databook, typical  $T_m$  for Ni alloys  $\approx 1450^\circ\text{C}$ . Hence hot working range  $\approx 590 - 1365^\circ\text{C}$ .

The temperature rise in deformation processing depends on: yield stress and strain (hence plastic work and heat input); thermal properties of the metal; component geometry; heat transfer conditions (to the tooling, coolant or atmosphere).

Significance of temperature rise:

- variations in temperature (and consequent deformation) in the workpiece lead to variations in microstructure (and hence properties) – e.g. in forging a complex shape, or start to end variations in rolled strip;
- severe surface deformation can cause local melting and a poor surface finish – e.g. extrusion;
- the temperature rise may be essential for a combined deformation and heat treatment – e.g. extrusion of heat-treatable aluminium alloys;
- excessive temperature rise leads to tool damage – e.g. in machining.

*Examiner's comments: Most people made reasonable attempts to explain each process, but were less good at making comparisons between them. Candidates were asked to 'discuss' criteria for deciding on material and process: a list of words was not sufficient here.*

4. (a)

(i) A simple method using cheap equipment. Heat supplied by manually-operated gas torch burning oxygen and acetylene (ethyne  $C_2H_2$ ). Filler rod supplied manually to melt pool. Excessive oxidation is prevented by shielding by the combustion gases (which can be adjusted to produce a reducing flame).

(ii) Two sheets of metal pressed together in a lap joint between two electrodes. A high electrical current is passed through the joint region, generating local heating and melting due to the resistance at the contact point. No extra metal needed, and no oxidation since the joint is internal to the sheets and so shielded from the air.

(iii) Laser welding uses a high-power-density beam as a heat source. This vapourises a small surface spot, giving high energy absorption from the beam. A deep narrow vapour cavity forms – a 'keyhole'. No filler is needed. Shrouding gas reduces oxidation.

A: Resistance welding, perhaps seam rather than spot welding. Easily automated, precise, little distortion or HAZ.

B: Laser used to fuse powder (can be fed coaxially around laser) onto surface: hard facing. Used for thick coatings (up to 10mm) for high-performance requirements.

(b) 5000 series Al alloys are non-heat-treatable, so are hardened by solid solution and by work-hardening. On welding, the material in the HAZ will recrystallise, losing strength. Nothing can be done to regain this strength, so if welded these alloys cannot be used for high-strength applications.

6000 series: Heat-treatable (precipitation hardened). Precipitates in the HAZ redissolve (reversion); natural aging at room temperature allows some of the strength to be regained after a few days.

Strength of weld metal determined by: nature and distribution of impurities and porosity, grain size and shape.

Further information: Factors which might be important are: thermal history of material, quench sensitivity, environment in which the structure will be used, fatigue.

*Examiner's comments: A lot of confusion in part (b). Very few knew what 5000 and 6000 series alloys were. Some guessed that one of the pair would be heat-treatable, but usually chose the wrong one. Hardly anyone mentioned work-hardening, so recrystallisation did not feature.*

3C1 / P4A 2009: Numerical answers

1. (a)
- (ii) Approx 3000°/min
- (iii) Critical diameters: Air: 2.0-3.5mm, Oil 45-50mm, Water 55-60mm
- (iv) 400HV