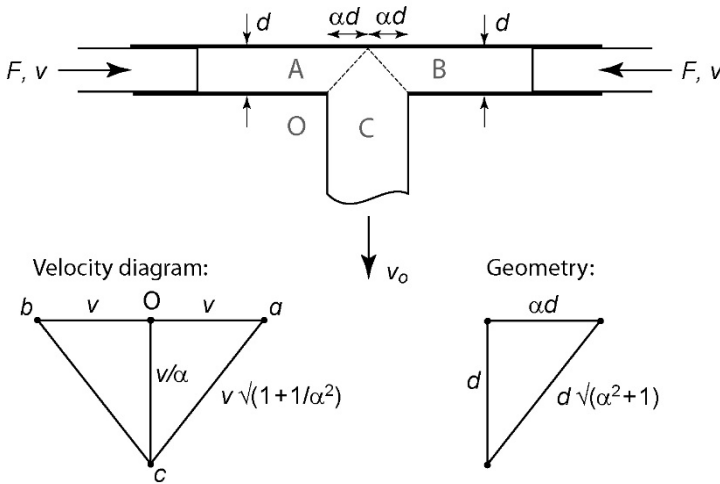


SOLUTIONS

Q1. (i, ii) From continuity of flow, conserving volume: $2 v d = v_o 2 \alpha d$ hence $v_o = v/\alpha$



Upper bound (per unit depth):

$$2 F v = 2 \cdot k \cdot v \sqrt{1 + 1/\alpha^2} \cdot d \sqrt{\alpha^2 + 1}$$

Hence:

$$F = kd \frac{(\alpha^2 + 1)}{\alpha} = kd (\alpha + 1/\alpha)$$

Minimum force when:

$$\frac{dF}{d\alpha} = 0 = 1 - 1/\alpha^2 \Rightarrow \alpha = 1.$$

(iii) Assuming all external work is converted to heat in the shear planes, and that the process is adiabatic (no losses to the dies etc), then estimate temperature rise ΔT from:

$$\text{input power} = \text{volume flow rate} \times \text{volumetric heat capacity} \times \Delta T$$

For unit depth: $2 F v = 2 v d \cdot \rho C_p \cdot \Delta T$ (where ρ is density and C_p is specific heat capacity)

$$\text{So } \Delta T = F/(d \rho C_p).$$

As d , ρ and C_p are constants, the temperature rise scales with α in the same way as F , i.e. $\Delta T \propto (\alpha + 1/\alpha)$, with a minimum at $\alpha = 1$.

In practice, low values of α mean a high outlet speed, while high values mean a low outlet speed. The assumption of adiabatic heating is more realistic for high outlet speed (low α) as the heat transfer timescale is longer compared to the material deformation timescale.

Friction with the die would increase the force (which would also fall with distance into die), and hence the power input to the workpiece, increasing the temperature rise (but also the heat losses to the die) before the material enters the shear zones, giving higher average ΔT in the output billet. The temperature rise would be non-uniform, due to the frictional heat input being at the surface, taking time to conduct inwards into the billet.

(iv) If the input speeds were different with a fixed ratio, symmetry in the deformation geometry will be lost – the output billet will emerge at an angle away from the vertical (in the direction away from the side in which the input speed is highest). The thickness of the billet will be less than $2\alpha d$, with a corresponding change in speed to maintain continuity.

If the ratio is varied, then the output direction continuously varies – the extrusion will curve. (Such a prototype process is currently under development, to enable curved sections to be produced directly by extrusion).

(b) In industrial extrusion of heat-treatable alloys, the temperature rise ΔT is used to take the material from the pre-heat temperature of the billet into the single phase region of the phase diagram, in order to extrude the material in a fully solutionised state. This is needed before quenching the extrusion on exit from the die, as the first stage of the ageing process (i.e. leaving a supersaturated solid solution, from which precipitation takes place at room temperature or on re-heating to the ageing temperature).

If the temperature rise is too low, some of the solute remains in coarse precipitates so on quenching the supersaturated solution is depleted. The ageing response is therefore reduced, giving a peak strength below the target value.

Assessor's comments:

(a) A simple upper bound analysis, though many failed to observe that the temperature rise scaled with α in the same way as the force. For the unequal speed case, most noted the loss of symmetry in the slip planes, but didn't recognise the required change in direction of the output billet.

(b) As is so often the case, many answered standard questions that they thought they knew about – the effect of an insufficient cooling rate (quench sensitivity), or the effect of a different ageing temperature – rather than the question being asked, which was about the effect of failure to fully solutionise the alloy during extrusion.

Q2. (a) (i) casting an Al-4wt% Si alloy:

During *mould filling* the radius:thickness ratio influences metal flow into the cavity, due to viscous drag against the mould wall slowing the flow. Heat conduction into the mould may also cause the onset of solidification, narrowing the channel further, and increasing the viscosity – from the phase diagram, this composition has a large freezing range (it is a “mushy freezer”).

Technical problem: high aspect ratio may lead to a mis-run: incomplete filling of the cavity.

Material change: use near-eutectic composition to improve fluidity.

Process changes: more or larger ingates to enable higher filling speeds; increase pour temperature to delay onset of solidification.

(ii) cold forging a Cu-Ni alloy:

Friction at the die-workpiece interface leads to a friction hill, but the effect of friction on the pressure distribution is magnified by the radius:thickness ratio.

Technical problem: load capacity of the machine may be exceeded, so target thickness cannot be met.

Material change: use a lower strength (more dilute) Cu-Ni composition (if lower strength in the final product is also acceptable).

Process changes: improve lubrication to reduce friction; consider warm or hot forging to reduce material strength (with a possible reduction in forming speed to reduce strain-rate, and thus reduce strength further).

(iii) quenching a carbon steel prior to tempering:

The aspect ratio influences the cooling rate at the point of slowest cooling – the cooling rate falls as aspect ratio increases, though reaching an asymptote when the heat flow becomes effectively 1D through-thickness. So if the aspect ratio is high, this will automatically give the slowest cooling rate for the specified thickness (quantified by the equivalent diameter).

Technical problem: cooling rate may be lower than the critical cooling rate (i.e. equivalent diameter is greater than the critical diameter for the carbon steel), so the required proportion of martensite is not formed through-thickness on quenching.

Material change: use a low alloy steel of similar carbon content to increase the hardenability.

Process changes: may be possible to switch from oil to water cooling to give some increase in cooling rate (and reduce the equivalent diameter).

(b) (i) Solidification of composition C_0 , shown on phase diagram (left):

- at T_1 , solid starts to form from the mould wall, with purer composition, kC_0

- excess solute rejected into liquid ahead of solid-liquid interface, and so compositions of solid rises steadily with distance, asymptotically approaching C_0 over initial transient region (top right)

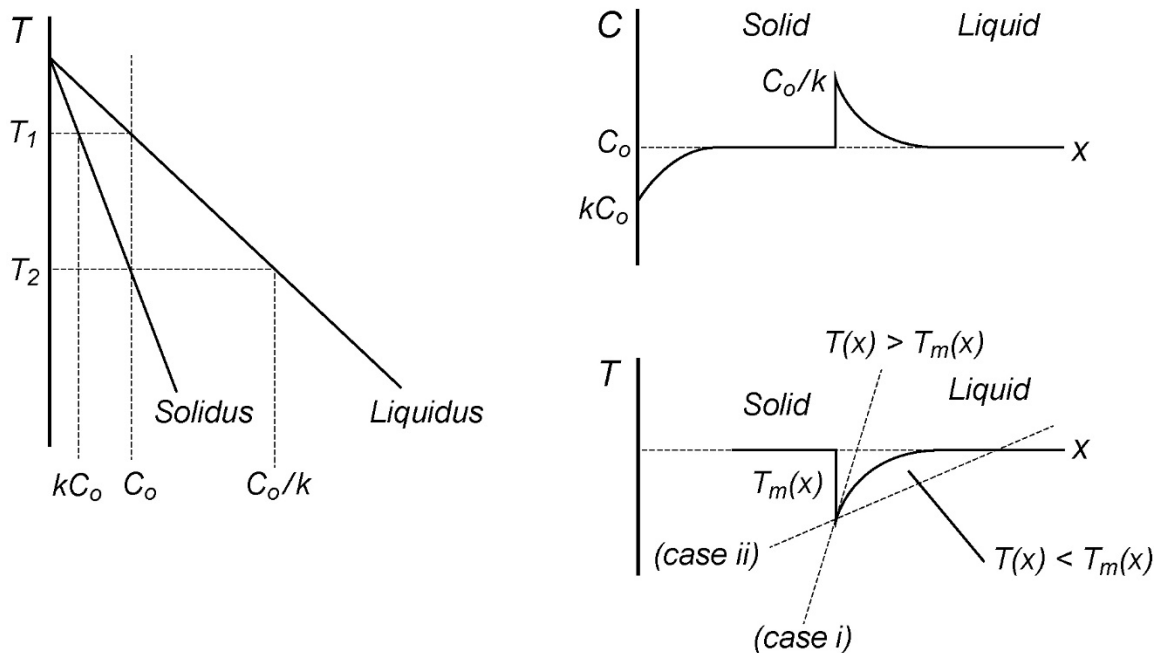
- approximating solidus and liquidus as straight lines, liquid composition at interface is then C_0/k , and steady-state is reached, with “bow wave” of solute progressing inwards at the interface (top right)

- variation of composition $C(x)$ in liquid leads to inverted curve for variation of the solidification temperature, $T_m(x)$ (bottom right)

- superimpose two temperature gradients at the interface:

Case (i): $dT/dx > dT_m/dx$: this means all liquid ahead of the interface has $T(x) > T_m(x)$: growth of solid is planar with a few *columnar grains*;

Case (ii): $dT/dx < dT_m/dx$: this means a region of liquid ahead of the interface has $T(x) < T_m(x)$: the growth of the solid interface is unstable, with *dendritic grains* advancing into this region – this is known as *constitutional supercooling*. Dendrites are finer scale “fir tree-shaped” grains during formation, but as they have a single crystal orientation, they form equiaxed grains when the dendrite arms meet as the last liquid solidifies.



(ii) Columnar grains sweep the increased concentration of liquid from the mould walls to the centre (together with dissolved impurities and gases) – this is macrosegregation, giving weak grain boundaries (often due to brittle phases forming) at the centre of the casting, and coarse porosity. Dendritic growth “traps” pockets of liquid between the arms, capturing excess solute, impurities and gases in small regions distributed throughout the casting (micro-segregation). Large numbers of small defects are much less damaging for strength and ductility.

(iii) The imposed temperature gradient determines the solidification speed and which regime of grain growth occurs. Factors affecting the temperature gradient:

- the choice of mould material: ceramic moulds conduct heat away from slowly than metal moulds.

- the pour temperature: increasing the pour temperature increases solidification time, and reduces the gradient by increasing the pre-heating of the mould near the casting, before solidification starts.

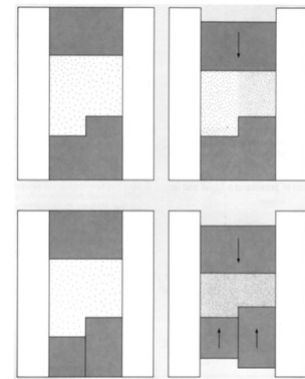
Assessor's comments:

(a) Many very good answers to each part, though rarely in all parts by the same student. There was also the usual imprecision in technical description, with cross-over from the wrong process or the wrong material. For forging many talked about high strain and work hardening – but there is no knowledge of the shape of the original blank. Surprisingly few mentioned that the increased load at high aspect ratio depends strongly on friction (i.e. via the friction hill). For steel heat treatment, many talked about reducing the quench rate to avoid cracking, when the goal is to form martensite (in order to temper), not to avoid it – so the solution is higher hardenability.

(b) Constitutional supercooling was well-explained, though the sketched figures were often poor (or non-existent).

Q3. (a) (i) A powder method is desirable to ensure uniform distribution of the high volume of carbide particles – and the high strength and abrasive particles would make forging difficult and expensive. Powder methods give low material wastage, and low porosity ensuring high strength.

(ii) Friction between powder and die results in variation in pressure and non-uniform compaction and density distribution, causing distortion. Compacts with variable section thickness tend to have a non-uniform density distribution if single die-sets are used (top of figure).



(iii) More uniform distribution can be achieved by:

- better lubrication between powder and die (e.g. add soap-like Zn-stearate as a solid-state lubricant when pressing iron powders)
- multiple punches, e.g. with differential speeds to give more uniform compaction strains (bottom of figure).
- change of process, e.g. hot isostatic pressing (HIPing).

(b) Any four of the following causes of crack formation in welds, and mitigation measures:

- Stress concentrations from weld geometry raising local stress levels (acting as crack initiation sites in fatigue).
Mitigation: grind weld bead surfaces smooth or concave, changing profile to reduce stress concentrations.
- Residual stresses from differential heating and cooling result in tensile stresses as high as the yield stress, enabling fatigue crack initiation at much lower stress amplitudes.
Mitigation: modify design of joint, clamping arrangements, welding process variables, and welding sequence (in multi-pass welds) – all to minimise thermal stresses from shrinkage and constraint during cooling.
- Porosity and cracks form in the weld metal due to solidification shrinkage, particularly if the grain boundaries at the weld centre are rich in impurities due to segregation.
Mitigation: induce residual compressive stress in weld metal by shot or hammer peening, to suppress crack initiation in fatigue.
- In some arc processes, impurity particles from the protective slag can be trapped in the molten metal, acting as crack initiators.
Mitigation: use of clean filler metal and good control of process variables to avoid entrapment of particles and segregation of impurities.
- Phase transformations in HAZ: the temperature rise in most of the HAZ takes the steel into the austenite range, giving a risk of brittle martensite formation on cooling (depending on the hardenability of the steel).
Mitigation: alloy choice to control hardenability – including choice of microalloyed steels to pin grain boundaries and prevent grain growth.

- HAZ grain growth: increases the hardenability of the steel, so higher risk of forming brittle martensite on cooling; a secondary effect is that the HAZ grain size at the fusion boundary determines the grain size in the weld metal, potentially giving rise to segregation problems and increased probability of martensite formation in the weld metal.

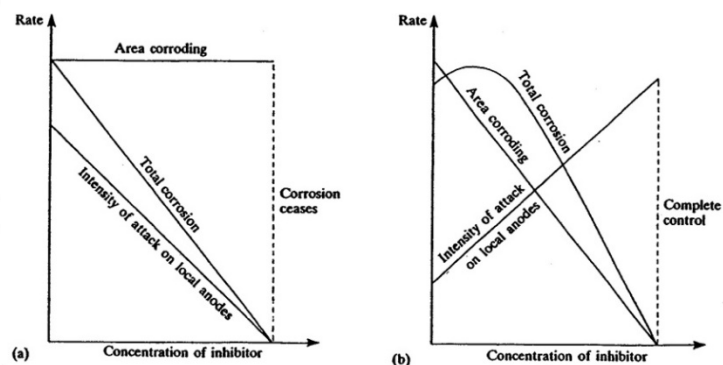
Mitigation: pre-heat components being welded to reduce cooling rate, or post-heat to temper any martensite formed.

- Hydrogen embrittlement: atomic hydrogen from decomposition of water in the weld diffuses rapidly, and leads to cracking in embrittled microstructures under tensile stress.

Mitigation: heat treat to remove hydrogen and avoid hydrogen embrittlement.

(c) **Cathodic** inhibitors work by forming surface layers which inhibit the cathodic reaction, and are intrinsically **safe** (figure (a)). The rate of corrosion (by the anode reaction) falls steadily as the cathode area is reduced progressively by chemical reaction with inhibitor, which forms an impermeable layer. If the concentration of inhibitor is insufficient to prevent corrosion completely then there will still be some corrosion, but the dissolution of metal is spread over the whole anode area and the rate of corrosion will be lower than in the absence of inhibitor. Both the total corrosion rate and the intensity of attack on anode areas (i.e. local corrosion) fall steadily as concentration of inhibitor rises.

The situation with **anodic** inhibition is very different (figure (b)). An example is sodium nitrite which forms a continuous protective film of iron oxide on anodic areas of a steel surface, acting as a barrier to further corrosion. The process of forming a protective film is called passivation. However, the inhibitor does this by encouraging oxidation of the steel, and unless the film is sufficiently thick and protective the corrosion rate of the steel is considerably greater than the corrosion rate with no inhibitor present at all. The anode area is reduced progressively by chemical reaction with inhibitor, but corrosion becomes increasingly intense at remaining anode areas. The localisation of the corrosion in the unprotected regions leads to pitting. The concentration of the anodic inhibitor must therefore be kept above a critical level.



Assessor's comments:

(a) Generally well-answered, though hardly anyone mentioned the difficulty of forging a hard alloy, only casting it.

(b) Good answers overall, with a better match between the problem being addressed and its solution than is sometimes the case in this paper: maybe it's better if they have freedom to state which problem they are talking about – though there were still those who talked about fixing generic corrosion or fatigue problems, with no reference to welding at all.

(c) Some excellent answers, but most very vague and based on fuzzy recall of general IB corrosion and protection, with no reference to forming protective layers in-situ.

Q4. (a) (i) Separate from other materials. Sort into different polymers. Clean to remove traces of other materials, including paper, metal, food. Cut up into pieces and put through screw extruder to produce pellets of polymer that can be used for making new products.

Importance: Polymers can't be purified to remove molecules or small particles of other materials, so what goes into the recycling mix determines the composition and properties of the recycled polymer. Common contaminants which can't be removed include: traces of other polymers, colouring, small molecules added to provide processing or property enhancement, food traces. Bigger fragments of other materials can be removed mechanically during the recycling process so not a problem.

Crucial steps for quality and retaining value are therefore sorting to generate single polymer waste streams, and cleaning.

Barriers to increasing recycling: virgin polymer prices are low (oil prices are low), and recycled polymers can only be sold for high prices if their quality is guaranteed. Recycling is expensive, with the stages listed above, plus transport, so the economics are generally unfavourable – significant investment needed in recycling facilities, plus improvements in sorting and cleaning technologies. Polymer recycling is also strongly influenced by the behaviour of the public in cleaning and recycling the correct polymers, and their perception of the value of doing so. (Possible additional note: situation is changing for some polymers as legislation requires use of recycled material in packaging, driving up prices for high-quality recycled polymer.)

(ii) Like-for-like mechanical recycling, maintaining quality, reduces the amount of polymer that needs to be manufactured, because products can be made successfully using recycled rather than virgin polymer. The embodied energy of polymers is high, so CO₂ savings can be large (1 tonne CO₂ per tonne of polymer). Material production savings must be offset against the energy/CO₂ required to collect, sort and clean the material, and then to extrude it to produce new material (normally in the form of pellets). Downcycling to other products, in which lower material quality can be tolerated, doesn't provide such large savings.

(b) (i) Heating polymer just above glass transition temperature allows it to change its shape. On cooling, mechanical properties are restored, but shape change is permanent. Polymers heated to significantly above T_g may start to degrade, becoming discoloured and then suffering degradation in mechanical properties. These effects are irreversible.

Other effects: crystallinity may increase, leading to higher strength and reduced toughness. This is irreversible unless the polymer is heated to above the crystallisation temperature to melt the crystals.

Mitigation: avoid high temperatures, or use polymer with higher T_g and decomposition temperature.

(ii) Example of reversible chemical effect: some grades of nylon absorb water: the small water molecules push between polymer molecules, causing swelling, and also changing the mechanical properties to reduce strength and increase toughness (increased plasticity).

Mitigation: use different grade of nylon, or different polymer, or avoid contact with water.

Example of irreversible chemical effect: chemicals that attack the polymer in some way, leading to three main different effects: reduction in chain length, depolymerisation, increase in cross-linking.

Mitigation: avoid exposure to specific chemicals.

(iii) Breakage of covalent bonds in the polymer, leading to three main different irreversible effects as above: reduction in chain length, depolymerisation, increase in cross-linking. Most commonly, UV exposure results in reduction in toughness so polymers crack.

Mitigation: either avoid exposure to UV, or make the polymer more resistant to damage by using a surface coating to reflect UV, or add particles to absorb or scatter UV in the polymer.

(c) (i) Shower tray:

Spray lay-up, using chopped fibre (glass) and polyester resin + catalyst mixed in a hand-held gun and sprayed directly into the mould or on to the structure. Spray lay-up gives a random 2-D fibre array: OK for relatively low load application. Delivers good surface finish needed on exposed side (in contact with mould), but can be rough on under side. Cheap process for batch production with a lot of customisation.

No clear alternative material to polyester-glass – need low-cost resin-rich composite. CFRP far too expensive for this application.

Wet layup process would improve stiffness and strength, using long fibre pre-preg, but would be slower in production and more expensive.

(ii) Cylindrical pressure vessel:

Choose filament winding – generally used for hollow (circular or oval sectioned) components. Continuous fibres (‘rovings’) are passed through a resin bath before being wound onto a mandrel in a variety of orientations. Can be very fast and economical. Resin content carefully controlled, and multiple fibre orientations can be precisely applied in layers to support the anticipated stresses.

Filament winding has limitations – particularly closing the cylindrical section at the ends. Fibre feeding equipment and inner mandrel can be expensive – but a layup process using vacuum bagging and autoclaving would be slow and expensive for a large hollow component of complex shape.

Material: choose continuous glass fibre, with low-viscosity epoxy or cheaper polyester resin (depending on required chemical and mechanical properties). Higher cost of CFRP may be justified in some cases.

Assessor’s comments:

(a) Poorly answered in IIA Engineering, but better in MET IIA (helped by other courses).

(b,c) Usual mix of good answers, and those with poor technical detail or missing parts of the question. In (c), some candidates proposed a bulk polymer as an alternative, in spite of the question stating that the product would be made out of a composite.