

Engineering Tripos Part IA Module 3C1  
Manufacturing Engineering Tripos Part I Module 3P1  
2010

q. 1. (a) The 'equivalent diameter' for a certain shape of body in the context of heat-treatment is the diameter of a long solid cylindrical bar which has the same cooling rate on its axis as the region in the body with the lowest cooling rate.

(b) (i) First significant effect of  $x/y$  is comparing zero and non-zero values.  $x/y = 0$  corresponds to a solid cylinder,  $x/y \geq 0.5$  is a hollow cylinder (with a hole diameter at least 1/3 of the outer diameter). For the solid cylinder, the limiting heat flow distance is the radius; for a tube it is half the wall thickness. Non-zero  $x/y$  leads to a large drop in  $f$  due to the quenching of the tube wall from both sides, inside and out. Then for non-zero values of  $x/y$ , the dependence on  $x$  rapidly disappears (compare  $x/y = 0.5$  to 1 to infinity) – this is because heat flow is governed only by the wall thickness once it is sufficiently thin (it is effectively the same as flat sheet of thickness equal to the wall thickness).

(ii) As  $y/z$  tends to zero, the asymptotes indicate where the length ceases to have any influence on cooling rate, (i.e. for thickness to length ratios  $<$  approximately 0.3,  $z$  effectively tends to infinity). Heat flow is 1-D through the wall thickness.

(c) For the cylindrical components:

(i)  $x = 10$  mm,  $y = 5$  mm,  $z = 10$  mm;  $x/y = 2$ ,  $y/z = 0.5$ .  $f = 1.38$ : error =  $-8\%$ .

(ii)  $x = 0$  mm,  $y = 10$  mm,  $z = 15$ mm;  $x/y = 0$ ,  $y/z = 0.67$ .  $f = 1.58$ : error =  $+5\%$ .

The purpose of quenching is to form a minimum proportion of martensite prior to tempering. To ensure this is achieved, the cooling rate in the "model" geometry should err on the conservative, i.e. lower than in the real component. Hence it is better to over-estimate the equivalent diameter, i.e. if a slightly larger component forms the target proportion of martensite, the actual component certainly will.

(d) (i) *Mn and Fe in heat-treatable aluminium alloys* Beneficial: both form second-phase dispersoids during casting and homogenisation, which can be used to control grain size on recrystallisation (via PSN, particle-stimulated nucleation).

Detrimental: during quenching after solution heat treatment, Mn and Fe containing dispersoids can nucleate non-hardening phases, using up solute that would otherwise remain in supersaturated solid solution for subsequent age hardening. Peak aged strength is then reduced (the effect known as quench sensitivity).

(ii) *Pb in carbon steels* Beneficial: addition of Pb used in free-machining steels, with Pb forming inclusions on grain boundaries promoting chip formation, enabling self-lubricating machining with lower cutting forces.

Detrimental: various aspects – Pb is expensive and environmentally damaging; also it lowers toughness and fatigue resistance of the steel.

(iii) *Ni in low alloy steels* Beneficial: increases hardenability, enabling quenching of larger components prior to tempering for optimum strength and toughness. (May also contribute directly to strength via solid solution).

Detrimental: higher hardenability leads to poor weldability, with the risk of forming martensite in the heat-affected zone, with consequent embrittlement.

Examiner's comments: The equivalent diameter definition and calculations were generally well done, though few candidates discussed the trends well in part (b). There was some vagueness about the effects of Pb and Ni in steels, with some candidates evidently just guessing.

q. 2. (a) Alloy shrinkage during solidification. Porosity (may be interconnected) found at grain boundaries and between dendrite arms (interdendritic regions) in last liquid regions to solidify. Cavities may form as shrinkage cracks in the final regions of a casting to solidify: thick sections typically. Reduce by mould design: ensuring there are reserves of liquid metal to allow feeding; design to allow castings to shrink without tearing; incorporate chills to promote early solidification in vulnerable places such as thick sections. In all cases porosity can be reduced by choice of alloy composition: minimising the semi-solid range by using eutectic alloy; using grey cast iron which has zero volume change on solidification.

Porosity from gas evolution. Dissolved gas comes out of solution as the metal cools. Can be reduced by vacuum de-gassing. Also can get steam evolution from damp moulding sand in sand-casting.

Turbulence during casting, entrapping air. Can arise at: in-gates where metal enters mould; section changes in mould cavity; during pressure die-casting. Reduce by careful design of moulds and feeding systems. Vacuum de-gassing before pressure die-casting reduces effect.

Cold shuts and misruns can also cause cavities, which can be avoided by good mould design, high fluidity and higher pouring temperature.

Post-casting processing: HIPing can be used in cases where the porosity does not penetrate to the surface of the component.

Plastic deformation (hot-rolling or forging) can be used to squeeze out porosity, but this is obviously inappropriate for net-shape castings. Not all alloys will be suitable either: some may be too brittle.

Heat treatment is ineffective as gas molecules do not diffuse sufficiently fast.

(b) Grain size: Small grains improve mechanical properties (yield strength and toughness). Reduce effects of impurity segregation to grain boundaries by increasing grain boundary area so reducing impurity concentrations. Grain size in steels influences hardenability. Chemical inhomogeneity can more easily be reduced by heat treatment alone in fine-grained materials. Large grain size – particularly eliminating boundaries normal to the stress axis - used to improve creep properties. Single crystals avoid the problem altogether.

Grain shape: Columnar grains may lead to interconnected porosity. Oriented, elongated grains may give good creep resistance (reduced g.b. area normal to the applied stress).

Control during casting: Inoculants to control nucleation; reduce pouring temperature to increase nucleation; vibrate mould to increase turbulence and displace dendrite arms which act as nuclei. Casting into a chilled mould increases nucleation so reduces grain size.

Post-casting control: Deformation and heat (or hot deform) to recrystallise.

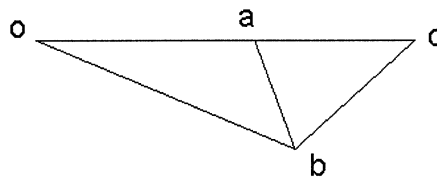
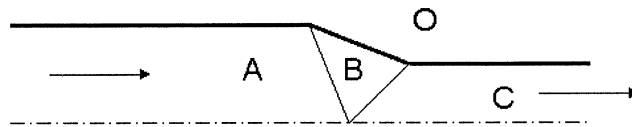
Single crystal turbine blade: investment casting with a 'pigtail': a helical cavity which selects one crystal from the chill zone by allowing only the most favourably oriented crystal to grow.

(c) Molecules become aligned by extension flow as they pass through a die. In die swell, molecules which had been aligned during extrusion coil up when material exits the die, leading to dimensional changes. This will mean that the extruded section is convex rather than square. Modify the die shape (concave section) to produce square section. Tolerances can be improved by: rapid quenching of the component after it emerges from the die to prevent melt swell, or by using a long die land to allow molecules to coil up before leaving the die. Another measure which is sometimes used is drawdown: tensioning of the extrudate while still hot after leaving die. Retaining tolerances may be difficult here.

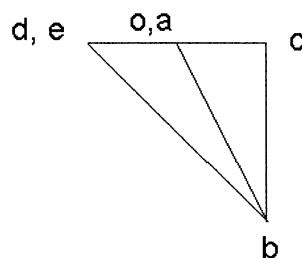
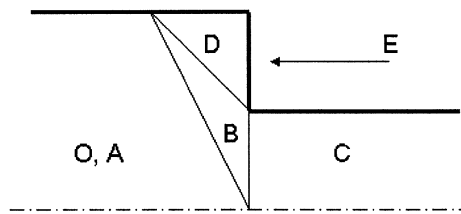
Examiner's comments: A straightforward question attempted by many candidates, with some excellent answers.

q. 3. (a) The upper bound method is based on the upper bound theorem which states that the plastic collapse load estimated by equating the rate of working of external forces to the internal rate of energy dissipation, for any compatible mechanism of deformation, will form an upper bound to the true load. We usually assume plane strain deformation and a rigid plastic material, with shear on internal shear planes.

(i)

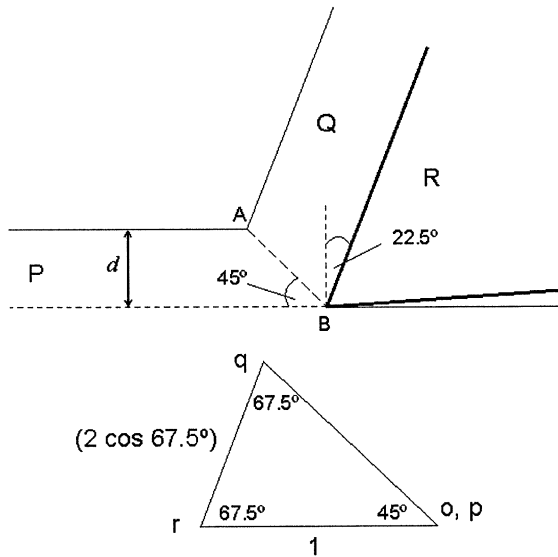


(ii)



(other possible deformation patterns and hodographs also acceptable)

(b) (i) Label regions of diagram P, Q, R and draw hodograph:



Assume workpiece to be stationary (i.e. origin O located with the tool R) and tool to be moving with unit velocity to the left.

$$V_{or} = V_{pq} = 1 ; V_{qr} = 2 \cos 67.5^\circ = 0.765$$

Equate rate of working of external force  $F$  to rate of energy dissipation on shear plane AB, for unit depth into diagram:

$$F \cdot 1 = k \cdot AB \cdot V_{pq} = k \cdot \sqrt{2} d \cdot 1$$

$$\text{Hence } F = \sqrt{2} dk$$

(ii) Sticking friction means that shear will occur at shear stress  $k$  over a length  $2d$  on the rake face of the tool. Equation becomes:

$$F \cdot 1 = k [AB \cdot V_{pq} + 2d \cdot V_{qr}] = dk [\sqrt{2} + 2 \times 0.765] = 2.94 dk$$

Hence  $F$  is now greater than  $2\sqrt{2} dk$

(iii) Assume that all the work goes into heating the chip, that the process is adiabatic, and that the temperature is constant throughout the heated chip.

Volume of chip deformed in unit time = depth of cut  $\times$  unit depth into diagram  $\times$  unit tool velocity =  $d$

Work done on system =  $F \cdot l$

Change in thermal energy =  $\rho dC\Delta T = F$

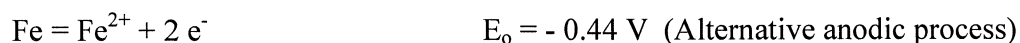
Hence  $\Delta T = F / \rho dC = \sqrt{2} dk / \rho dC = \sqrt{2}k / \rho C$

Substituting data given,  $\Delta T = \sqrt{2} \times 500.10^6 / (7900 \times 450) = 199 \text{ K}$ .

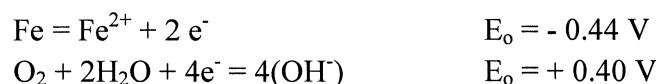
(iv) Friction on the rake face of the tool is a very important source of heat, which is localised on the tool and thus leads to significant heating of the tool: it acts as a fixed heat source (relative to the tool) whereas dissipation in the shear zone (and the frictional heating) moves relative to the chip. The volume of material being heated in the tool is thus much less than that in the chip, and the temperature rise tends to be higher. The rise in tool temperature can lead to thermal softening of the tool, thermal cracking and/or oxidation of the tool material. The frictional power dissipation depends on machining speed and so can be reduced by cutting at a lower speed. Cutting fluids (typically oil/water emulsion) are beneficial both to lower the friction (as a lubricant) and also to transfer heat away from the cutting zone.

Examiner's comments: This largely quantitative question was well done by nearly all the candidates who attempted it.

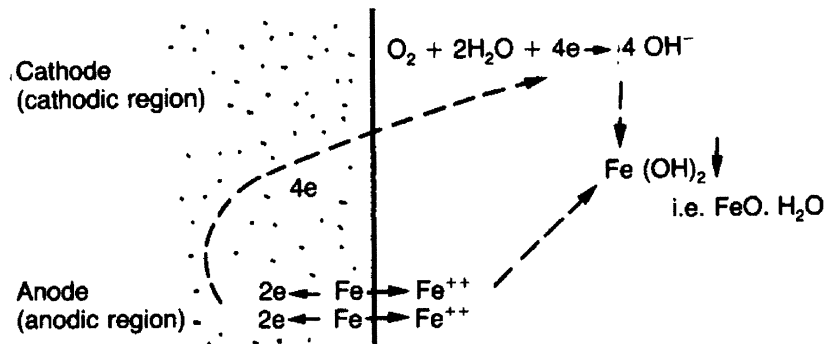
q. 4. (a) Galvanised iron is coated with a thin layer of zinc. The zinc dissolves to form  $\text{Zn}^{2+}$  ions, releasing electrons. The electrons flow into the iron, which becomes the cathode. On the iron surface, oxygen dissolved in the water reacts with water to form hydroxyl ions  $\text{OH}^-$ . This uses up electrons, so the corrosion of the zinc continues. If the zinc (with the lower SEP) were not present, the anodic reaction would be oxidation of the iron, which would therefore corrode. The presence of the zinc protects the iron.



Corrosion when paint films have been disturbed is an example of differential aeration or concentration corrosion. Corrosion (rusting) in water in the presence of oxygen takes place by the reactions (as above):



These two reactions occur at different regions of the steel surface, depending on the local oxygen concentration, and electrons are transported between the two by conduction through the metal.



The oxygen levels are highest directly under the crack in the paint film, and the lowest oxygen levels are under the paint film next to the crack. Corrosion (the anodic process) will be concentrated here where the oxygen concentration is lowest, so cracks spread under the paint film.

(b) (i) Wet lay-up, hand lay-up.

Resins impregnated by hand (using rollers or brushes) into fibres (generally in the form of cloth of some sort). Only suitable for low-viscosity resins (may be warmed). Left to cure at room temperature.

Advantages: Reasonably cheap, technique easily taught, versatile. Suitable for a very wide range of fibres and resins. Good for one-off jobs.

Disadvantages: Quality of composite very dependent on skill of operator. High fibre volume fractions difficult to achieve. Health hazards from low-viscosity resins and styrenes.

Starting from pre-preg sheets

Continuous fibre composite articles are often made by stacking sheets of fibre plus uncured resin; the stack is heated and pressed to shape (press moulding), and is generally cured under heat and pressure. Sheets may be woven or unidirectional (e.g. laminae produced by pultrusion).

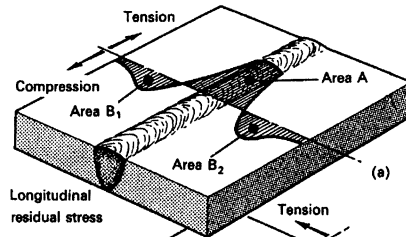
(ii) Once the fibre-matrix interface is exposed to a damp or wet atmosphere, there is the possibility of water wicking in along the interface and penetrating deep into the composite structure. Matrix and fibre may both degrade, swelling can result from cracking of the fibre-matrix interface.

(c) (i) Thermal residual stresses result when only part of a component is heated, as usually occurs in welding. The material close to the weld (HAZ) is heated and expands. The hot region is constrained by the cooler surrounding material away from the weld pool, and so is put into compression. However, being hot, its yield stress is reduced, so it can plastically deform relatively easily (and it may also creep). Where the material can flow to depends on the geometry. When the region cools, there is contraction, and the HAZ and weld pool are put into tension. Stresses also arise

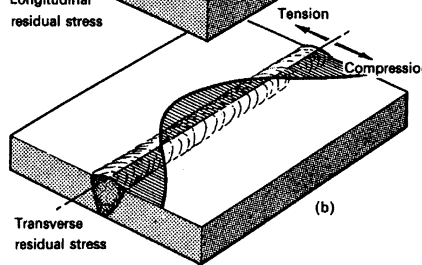
because of solidification of the molten metal in the weld pool: this will increase tensile stresses in the HAZ.

Tensile stresses are generally of the order of the material yield stress, and are balanced by compressive stresses elsewhere.

*Distribution of residual stresses across weld*

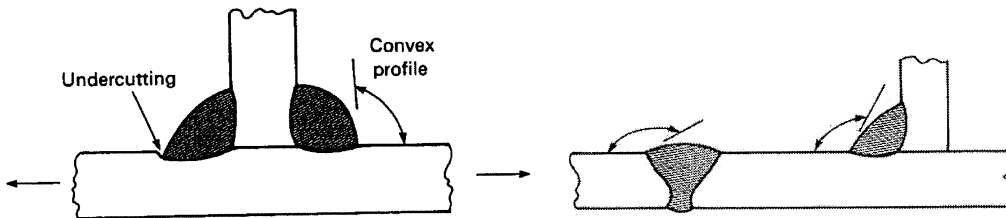


*Distribution of residual stresses along weld*



Reducing stresses: Pre-heat the whole component; post-weld heat-treat to allow stresses to relax.

(ii) Stress concentrations arise at any section change or change in profile, such as are usually found at weld beads. They can be reduced by grinding the beads flat, or grinding our convex profiles to make them concave thus reducing the contact angle. Surface grinding marks can themselves act as stress concentrators.



(iii) Occurs in the HAZ in unstabilized stainless steels. Chromium reacts with carbon to form carbide particles which precipitate on grain boundaries. This leaves a chromium-depleted region around grain boundaries, which means that chromium oxide (which normally acts as a protective layer on the steel surface) cannot form, leaving the grain boundary regions vulnerable to corrosion. These regions will form localised anodes, and deep cracks can form quickly.

Problem can be avoided by using steel of a different composition: stabilised by the inclusion of small amounts of niobium or titanium, which form carbides preferentially, so leaving the chromium in solid solution and able to form the oxide surface layer.

Examiner's comments: Straightforward material from the course but a few candidates demonstrated little recall or understanding. Some showed little awareness of differential aeration in part (a). 'Weld decay' was correctly described by only a few candidates.

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May 2010



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*Numerical answers*

q. 1. (c) For the cylindrical components:

(i)  $f = 1.38$ : error =  $-8\%$ .

(ii)  $f = 1.58$ : error =  $+5\%$ .

q. 3. (b) (ii)  $F = 2.94 dk > 2\sqrt{2} dk$   
(iii)  $\Delta T = 199 \text{ K}$

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