

2012 Manufacturing Engineering Tripos IIA Paper 1: Materials into Products
Prof Ian Hutchings

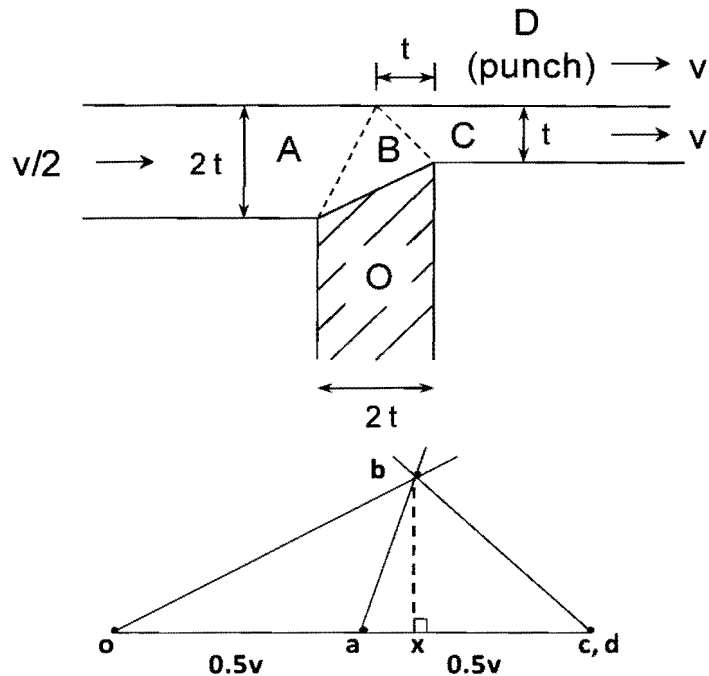
3C1, 3P1 2012 Solutions

1. (a) Shaped section rolling uses a series of profiled rolls, often with the sequence of rolls mounted on a common axis in a reversing mill. The rolled stock is translated across between successive passes. In a single roll stand, there may be a combination of horizontal and vertical axis rolls to define the 2-D profile. Either way, the metal flow is constrained vertically and laterally to generate the section while reducing the cross-sectional area and increasing the length of the stock.

Choice of process and material (any two comments accepted in each case):

- (i) sand cast bronze:
- Cu-based alloy much more expensive than low carbon steel;
 - longest (5 m) sections beyond reasonable size for sand casting, and variable length will add cost as multiple patterns needed as well as a new mould for each casting produced;
 - feeding metal into such a long mould would be very difficult;
 - there is wastage associated with runners, risers, sprue etc.;
 - for a prismatic section and for variable lengths, the obvious solution is a prismatic process capable of producing at least 5m lengths, with each part cut to length
- (ii) three low alloy steel strips, with longitudinal arc welds to form the shape:
- low alloy steel more expensive than low carbon steel;
 - strip itself will be cheaper, and easily cut to length, but the need for many long welds to build up the profile is likely to be slow and expensive compared to producing the profile in one go;
 - welding this alloy adds many quality issues: control of residual stress and distortion, and the avoidance of embrittlement in the HAZ or weld metal (higher hardenability steel);
 - welds may exhibit fatigue failure and/or act as sites for corrosion;
 - again, prismatic section cut to length is better.

(b) Incoming sheet has half the velocity of punch and outgoing sheet (by continuity through the die), so there is slip between A and D (but not C and D). There is no friction on AD (given).



From hodograph:

$$bx/ax = 2 \quad bx/cx = 1 \quad bx/ox = 0.5 \quad ox = 0.5v + ax$$

Hence: $bx = 0.5ox = 0.5(0.5v + ax)$, but as $bx = 2ax$, $2ax = 0.5(0.5v + ax)$, so $ax = (0.5/3)v$

Hence: $bx = cx = 2ax = v/3$, and $ox = 2v/3$

Thus: $ob = \sqrt{(4/9 + 1/9)}v = v\sqrt{5/3}$ and $bc = v\sqrt{2/3}$ and $ab = \sqrt{(1/36 + 1/9)}v = v\sqrt{5/6}$

Interface	Length ($\times t$)	Relative velocity ($\times v$)	Interface stress ($\times k$)
	Internal energy ($\times tvk$)		
AB	$\sqrt{5}$	$\sqrt{5/6}$	1
OB	$\sqrt{5}$	$\sqrt{5/3}$	1
BC	$\sqrt{2}$	$\sqrt{2/3}$	1

$$\text{Total: } (10 + 20 + 8) / 12 = 38 tvk / 12$$

$$\text{External work done (per unit width)} = Fv = 2 \times (38 tvk / 12)$$

(n.b. double as there are two identical deformation zones)

$$(i) \text{ Hence } F = 38 tk / 6 = 6.33 kt$$

$$(ii) \text{ The tensile stress is } F / 2t = 3.17 k$$

This is greater than the tensile yield stress of the material in plane strain (which is $2k$), so that the material will fail in tension outside the die. The proposed upper bound deformation pattern will not operate, and the deep-drawing operation cannot be carried out (unless there is a different deformation pattern giving a sufficiently lower upper bound, or the die is lubricated to reduce the friction on OB).

Examiner's comments: Comments were made by some candidates on rolling of sand cast and welded rails, despite the question saying that these were alternatives. The hodograph was generally well derived: errors in part (b) were mainly through omitting sticking friction at the die or failing to double the force to take account of symmetry. Many of those who successfully derived the force and compared it with $2k$ failed to see the significance of their results: that the proposed deformation mechanism would not operate. No candidate commented (as they might have done) that if the friction could be reduced then the process might be operated successfully.

2. (a) Chvorinov's rule: solidification time $t_s \propto (V/A)^2$

where V = volume and A = surface area of the casting.

(i) For sphere of radius R : $V = \frac{4}{3} \pi R^3$, $A = 4 \pi R^2$,

$$\text{so } (V/A)^2 = (R/3)^2$$

(ii) For cylinder of radius R , and length $L = 20R$: $V = (20R) \pi R^2$, $A = (20R) 2 \pi R + 2 \pi R^2$,

$$\text{so (neglecting ends) } (V/A)^2 = (R/2)^2$$

(iii) For rectangular plate of dimensions $L \times 10L \times 100L$:

$$V = L (10L) (100L), \quad A = 2 \times [(10L \times 100L) + (100L \times L) + (L \times 10L)],$$

$$\text{so (neglecting sides) } (V/A)^2 = (L/2)^2$$

The solidification time is proportional to the square of a simple fraction ($1/3$ or $1/2$) of the shortest dimension of the part. This reflects the dominant heat conduction distance from the centre of the part to the surface. As $\text{time} \propto (\text{heat flow distance})^2$, this is governed by the thermal diffusivity of the material, a , i.e. Chvorinov's rule is consistent with $x = \sqrt{at}$.

In heat treatment of steel, the equivalent diameter gives the diameter of a long cylinder that has the same *cooling rate* at the point of slowest cooling. It is expressed as a multiple of the shortest heat conduction distance to the surface, which is directly analogous to the scaling found above for Chvorinov's rule. Solidification time is a different criterion to cooling rate, but clearly they both scale with $(\text{heat flow distance})^2$.

(b) (i) TiB_2 powder acts as an *inoculant* in Al alloy castings, stimulating extensive heterogeneous nucleation of the initial solid on solidification. Each nucleus becomes a grain, reducing the grain size. The important physical behaviour is the competition between the surface energies of liquid-inoculant, solid-inoculant, and solid-liquid.

This is captured by the *wetting angle* at the boundary of the solid-liquid interface on the inoculant surface. A low angle is most effective – solid rapidly spreads over the particle, so that the stable nucleus radius is exceeded with a lower volume of solidified liquid.

(ii) Mn and Cr are elements that form dispersoids in Al alloys (second phase particles). The average size and volume fraction of dispersoids may be changed by varying the homogenization treatment after initial ingot casting. The physical effect of the dispersoids is that in hot worked Al alloys, they act as nuclei for recrystallisation (in the solid state, after forming) – so-called *particle-stimulated nucleation* (PSN). Each nucleus becomes a recrystallised grain, giving a grain size that is dependent on the Mn and Cr content and homogenization treatment (even if the deformation and annealing conditions are exactly the same).

(iii) Magnesium poisons the growth of brittle flake graphite, leading to spheroidised graphite nodules and higher strength and ductility (as premature fracture is avoided in tension). The physical effect of poisoning is that the trace alloy addition blocks ledge growth of the non-metal phase, leading to a finer and more rounded morphology of the brittle phase.

(iv) The metal blocks in the wall of the mould are chills, designed to accelerate the cooling rate in this part of the casting. By solidifying this region first, feeding of liquid metal is improved, avoiding shrinkage problems such as macroporosity, which are associated with trapped volumes of liquid solidifying with no route for the dissolved gas to escape.

Examiner's comments: A popular question with some good answers. In part (a) candidates commonly found it difficult to make sensible comments and draw a meaningful analogy with the concept of equivalent diameter. The occasional student did not know the formula for the surface area or volume of a sphere. In part (b) there was generally good recall of lecture material. The extent of explanations offered in the answers varied widely, and some were confused about the role of Mn and Cr in Al alloys.

3 (a) Injection moulding involves: melting the polymer in an electrically-heated screw feeder (similar to a screw extruder – heat is also generated by friction and viscous flow in the extruder); injection of the polymer melt into a closed mould cavity, by axial movement of the extruder screw or by a separate injection piston; cooling of the part in the mould; removal of part from the mould and detachment of waste material (runner, sprue). Main difference in behaviour between semicrystalline and amorphous polymers is in volume change associated with cooling: crystallization involves a larger volume reduction.

(i) Higher injection pressure gives better surface detail/precision, and helps to compensate for shrinkage, so is especially useful for semicrystalline polymers

(ii) Longer hold-on time also counterbalances shrinkage and so is more beneficial for semicrystalline polymers; it will also lead to a longer cycle time and lower production rate

(iii) Higher mould temperature gives slower cooling, and thus greater crystallinity in a semi-crystalline polymer (and larger crystallites) – thus greater stiffness and more shrinkage. It will also give less molecular alignment.

(b) (i) Molecular chain alignment results from extensional flow e.g. through a constriction. Polymer molecules are randomly coiled in the melt, but these chains can become extended which leads to molecular alignment. So alignment in the final part is favoured by flow through constrictions and rapid cooling (e.g. low mould temperature and/or thin section) so that the chains cannot randomise again.

(ii) Residual stress usually originates from differential cooling. The polymer close to the mould wall solidifies first, with material in the centre still molten. This material then cools and shrinks, putting the surface regions into compression and leaving the core under tension.

(c) (i) Chain alignment can give much higher stiffness and strength in the direction of the chains – this is exploited for example in polypropylene strapping (which is extruded and cold-drawn), extruded/drawn nylon monofilament, stretch-blow moulded bottles and in moulded-in hinges in some injection-moulded components (where the fatigue life in bending can be very high).

(ii) Residual stress can lead to warping and distortion of the part if the stress distribution is unbalanced, and can also lead to slow crack growth, crazing and environmental stress cracking for parts exposed in certain environments.

(d) (i) Amorphous thermoplastics are particularly susceptible to crazing and environmental stress cracking, when exposed to certain chemicals. An injection-moulded bowl will contain residual stress, and that was probably also responsible for the final fast fracture when one crack reached critical length in the stress field. The fact that the damage initiated at the inside of the bowl suggests that some ingredient in the contents was responsible. Although in principle this might be avoided by reduction in residual stress (e.g. by lower cooling rate) and/or by some protective coating inside the bowl, in practice a change of polymer to one less susceptible to ESC (e.g. a semi-crystalline polymer) is needed.

(ii) Thermal cycles in GFRP cause differential thermal expansion of the fibres and matrix (glass having a much lower CTE than epoxy resin) which causes eventual fatigue failure at the fibre-matrix interface. This will be exacerbated by capillary wicking of water along the interface, which may also lead to fibre fracture (by slow crack growth in the glass in the humid environment). These processes lead to progressive reduction in stiffness. To avoid, we need better fibre/matrix bonding, better sealing to avoid water penetration, use of other fibres (eg carbon or aramid = Kevlar) which do not suffer from slow crack growth in water.

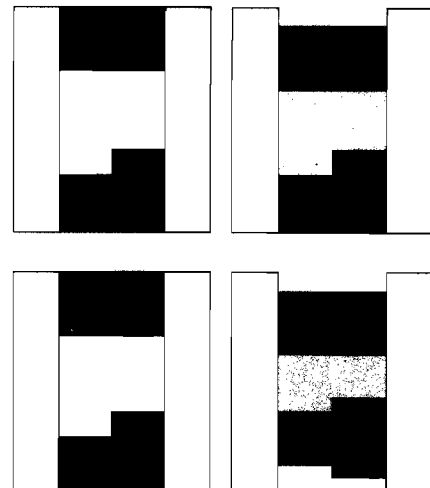
(iii) Exposure on outside of building suggests photodegradation: breakage of covalent bonds particularly e.g. by UV photons in sunlight. May lead to three distinct effects: reduction in polymer chain length; depolymerisation (i.e. chain breakage leading to monomer formation); or increase in cross-linking. Often some discoloration. Permanent damage; mechanical properties affected in various ways specific to the damage type. Polymer can be made UV-resistant either by surface coatings or by introducing scattering features into the structure (crystalline

regions of the polymer, or white pigment particles), or absorption features (coloured or black pigment particles).

Examiner's comments: Popular question showing generally good recall of course material. Some misunderstood the meaning of 'hold-on time' and some did not appear to appreciate that crystallization of a polymer involves an increase in density. Some candidates lost marks by failing to answer all parts of the question.

4 (a) Process involves: mixing powder + additives; filling shaped die with powder; pressing powder in die to form 'green' part; (optional – machining of green component to form additional features); sintering (typically $0.7 - 0.9 T_m$); then either cool followed by reheating to austenitise, then quench to form martensite, then temper; or quench direct from sintering furnace, then temper. Raw materials will be iron powder; graphite (as carbon source for steel – up to 1 wt%); usually copper (1-4 wt% - adds strength and prevents shrinkage during sintering); lubricant/binder (e.g. stearic acid, zinc stearate – allows powder to flow more easily and fill die better, reduces punch/die friction, improves strength of green part). Disadvantages of PM route compared with machining from bar stock: component size limited by press capacity (up to 1 kg steel typical maximum size); high cost of punch/die means only suitable for large production volumes; limited to geometries which can be made with uniaxial die/punch (possibly with additional green machining); still some residual porosity so mechanical properties not as good as a component from wrought bar-stock.

(b) Uniformity of properties will be determined by uniformity of powder packing in the die, which feeds through to porosity and final mechanical properties in sintered part. Good lubrication is needed to reduce friction between powder and die/punch: so need a lubricant in the powder blend. If component has a complex shape then need to use multiple punches to ensure even packing. Illustrate by sketch of split punches showing uneven compression for a single stepped punch.



(c) (i) needs high strength so needs highest density possible after sintering. For high packing density of powder, select particle size distribution (small particles to fill the gaps between larger) to optimise, and use high compaction pressure in die. Use high sintering T and long time to minimize residual porosity.

(ii) Bronze filter needs high and controlled porosity, so use spherical powder (air atomized) with narrow size range (e.g. by sieving). Fill die and apply *minimal*

pressure, then sinter at a relatively low T for a short time, but enough to cause interparticle bonding and produce sufficient strength. (In practice such filters are made by pouring powder into graphite dies and are sintered in the die so that the low green strength is irrelevant, but that process was not covered in lectures)

For higher strength in gear teeth in (i), could introduce cold work/compaction by forging the component after sintering: either cold or hot (sinter-forging). Other options include surface engineering e.g. by carburising or transformation hardening (e.g. by laser, induction or flame treatment).

Examiner's comments: Reasonable recall of the process steps in part (a) although some suggested that heat was applied during pressing, and others thought that martensitic steel powder would be used as the starting material. Weaker candidates regurgitated lecture material and failed to address the precise questions being asked.

IMH
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