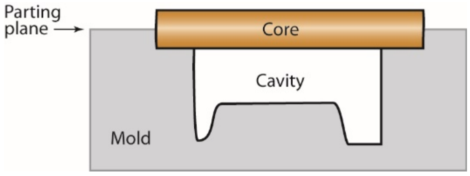
ENGINEERING TRIPOS Part IIA, MODULE 3C1 APRIL 2019

MANUFACTURING ENGINEERING TRIPOS Part IIA, MODULE 3P1

1. (a) (i) The *parting plane* needs to cut the capstan through the centre on its vertical axis – in practice, it would be cast on its side, with a horizontal parting plane.

To make the central hole, a cylindrical *core* would be located on the parting plane, and supported in the mould, i.e. using a core that is longer than the capstan, as shown in the sketch.



The LH design is preferable due to:

- the taper angle on the flanges makes it easier to remove the pattern from the sand mould, without damaging the mould;
- the radius on the corners improves metal flow, avoiding turbulence and mould damage;
- the stress concentration at the corners is lower, reducing the risk of hot tearing during cooling.

(ii) Working in millimetres:

Volume: $V = \frac{\pi D^2}{4} \times L = \frac{\pi(110)^2}{4} \times 150 = 1426 \times 10^3 \text{ mm}^3$

Surface area:

$$A = 2 \times \frac{\pi D^2}{4} \times L + \pi D L = 2 \times \frac{\pi(110)^2}{4} \times 150 + \pi \times 110 \times 150 = 70.8 \times 10^3 \text{ mm}^2$$

Hence solidification time is approximately:

$$t_s = C\left(\frac{V}{A}\right)^2 = 1.0 \times \left(\frac{1426}{70.8}\right)^2 = 405 \text{ s}, \text{ about 7 minutes}$$

Grain structure (e.g. columnar vs. dendritic/equiaxed), affecting distribution of impurities and porosity at macro scale;
Grain size and dendrite arm spacing, affecting distribution of impurities and porosity at micro scale.

(iii) Mechanical properties of forgings typically superior to casting: no porosity, finer and more uniform microstructure.
Forging would use different Al alloy – potentially heat-treatable, and thus higher strength and lower wear rate than casting alloy.
Forging would give better dimensional accuracy and surface finish.
Forging would use a closed die with a solid billet, so an additional machining step needed (with additional cost) to make the central hole bored afterwards.
Potential reduction in cost per capstan, depending on batch size: forging favoured over sand casting if batch size is large.

(b) Any four of the following:

- avoid the need for moulds or dies – low tooling costs; potential to integrate AM deposition head with machining head on one machine
- (mostly) net-shape processes – low material waste
- unlimited form freedom and complexity – revolutionary component geometries, and easily customised
- integration of parts into single component, reducing part count and assembly processes – savings in cycle times
- both of the above may enable lightweighting and lower material usage
- automatically integrates CAD with manufacturing instructions, readily distributed globally
- reduction in need to maintain inventories of spare parts
- vary composition across components

Example metal AM process, powder bed fusion: scanning pulsed laser used to sequentially melt spots of material from a pre-deposited powder.

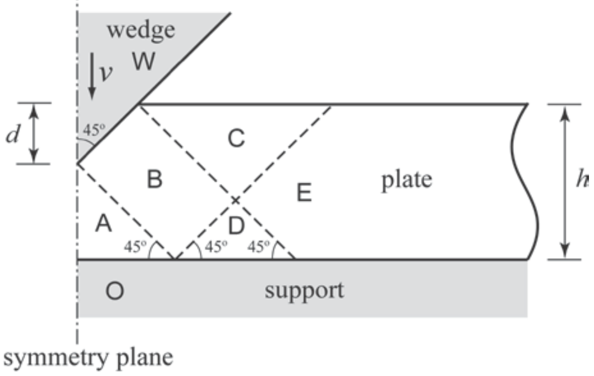
Example polymer AM process: polymer extrusion or jetting, intermittent deposition of droplets of molten polymer.

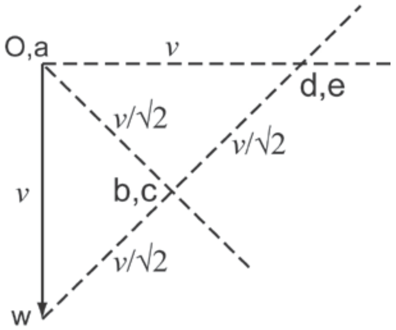
Both processes build up solid with large numbers of small droplets that solidify, often somewhat flattened in a plane normal to the build direction. This leaves a degree of porosity, and also a large number of interfaces between the layers where the bonding may be weaker (e.g. due to trapped oxide in metals). This is detrimental to mechanical properties, particularly in the build direction (normal to the layers).

(Q1 Casting / hot forging / additive manufacturing: high number of attempts, above average mark.

In (a), many suggested horizontal parting planes that would not actually release the pattern from the mould; in the calculation, many omitted the area of the cylinder ends, assuming the long cylinder result from lectures, or made allowance for the core-filled hole, which doesn't help with cooling; in (a,iii) several unthinking answers simply trotted out the relative performance of hot forging from the notes, where it is in comparison with cold forging, not sand casting; others gave generic advantages/ disadvantages which had no relevance to making the component in the question. AM answers in (b) were uniformly good.)

2. (a) (i)





	Length	Relative velocity	Length × velocity
AB	$(h - d)\sqrt{2}$	$v/\sqrt{2}$	$v\,(h - d)$
BW	$d\sqrt{2}$	$v/\sqrt{2}$	$v\,d$
BD	$d\sqrt{2}$	$v/\sqrt{2}$	$v\,d$
CE	$(h - d)\sqrt{2}$	$v/\sqrt{2}$	$v\,(h - d)$
		Sum =	$2\,v\,h$

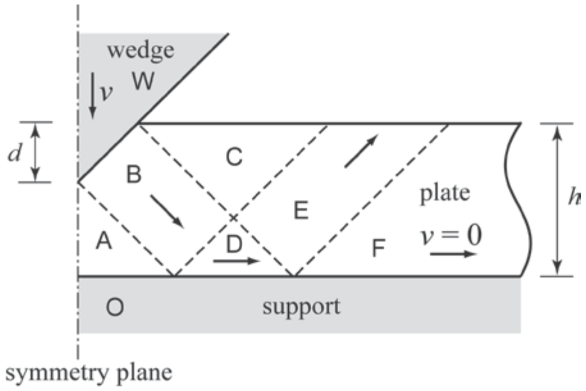
For unit depth, and one side of the symmetry plane:

$F/2 \times v = 2\,v\,h\,k$

so: $F = 4\,h\,k$

(ii) The external power is dissipated through the interfaces AB, BW, BD, CE. There is no material flow through the interfaces AB and BW, while material flows through BD and CE at velocity $v/\sqrt{2}$ (dissipating half the power vh). So the heating of DE relative to BC could be estimated (i.e. assuming adiabatic heating, and equating power in to volume rate × heat capacity × temperature rise). But half the power is applied at AB, BW giving a temperature gradient away from these interfaces down the plate, requiring a different type of analysis. Time-scales for conduction could be compared with the cutting time scale, to assess the extent of heat re-distribution, i.e. heat conduction within the deformation zone has a time-scale $t \approx h^2/a$, where a is the thermal diffusivity; that for cutting is $t \approx h/v$.

(iii) With sticking friction between the plate and the support, assume the plate away from the tool does not move at all, so additional slip planes are needed to enable the plate top surface to move upwards, e.g.



(b) (i) Aqueous corrosion of iron: $Fe \rightarrow Fe^{2+} + 2e^-$ and $H_2O + O + 2e^- \rightarrow 2OH^-$

Bolted joints may trap water in the lap region and bolt hole, giving *crevice corrosion* due to differential aeration. Within a crevice, the trapped water is quickly depleted of dissolved oxygen, localising the anodic reaction to the crevice, while the surrounding plate provides the cathodic reaction (over a much larger area).

(Note that both plate and bolts are mild steel, so galvanic corrosion is not an issue)

Best practice in design:
– orient the joint to enable water run-off, avoiding water traps adjacent to the plate overlap
– close the edges of the lap joint with a sealant to keep water out
– use galvanised steel or paint to keep water away from the mild steel to block the cathodic reaction

(ii) Advantages of fusion welding: continuous welds at edge of overlap seals the joint, preventing water ingress. Greater flexibility in orienting the joints in any direction.

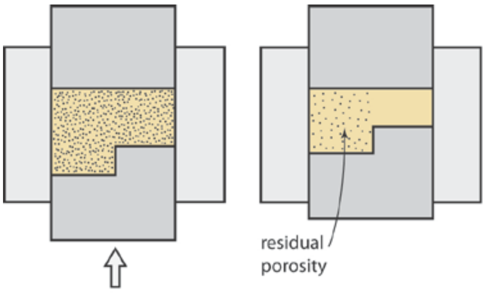
Disadvantages: more expensive, and requiring more clamping and support during assembly; cannot be disassembled for repair or at end-of-life.

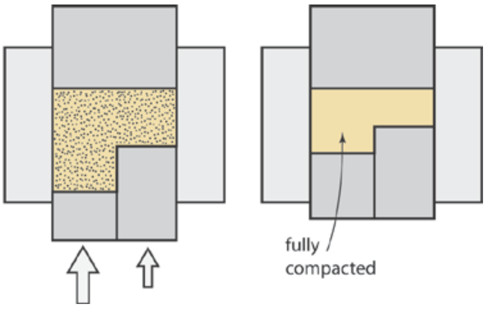
(Note that mild steel not expected to suffer from problems of HAZ softening or embrittlement or localised corrosion)

(Q2 Upper bound plasticity / aqueous corrosion of joints in steel sheet: low number of attempts, average mark.

Common errors in (a) were to use F instead of F/2, and failure to recognise that two pairs of blocks move together [B+C and D+E in the 1st figure]; most had little idea how to propose an alternative set of slip bands that were geometrically compatible, or recognised the need for material to be forced upwards if the plate did not slip over the support; in (b), many talked generally about rust, with no specific reference to the effect of the joint.)

3. (a) Full compaction requires the same vertical "strain" to be applied to the powder. A single-part die will compact the shallower region first, leaving the deeper region porous. A two-part die allows a different displacement in each half, giving the same ratio of initial:final height.





(b) Assume that there is no flow of material between the two parts of the die, so compaction occurs uniaxially in each half, i.e. the volume of solid is separately conserved in each half, and the same vertical strain is applied.

The vertical dimension of the part therefore scales inversely with its relative density (as the area is fixed in each of the two parts of the component). The final relative density is 97%. Hence the depth of powder in each half of the mould needs to be 97/50 × final vertical dimension. The filled cavity depths are therefore 38.8 and 23.3 mm.

(c) (i) Manganese, Mn: primarily to react with S during solifidification to avoid formation of brittle FeS on grain boundaries (risking embrittlement); residual Mn in solution also contributes to increasing hardenability.

Chromium, Cr: increases hardenability, and corrosion resistance

Tungsten, W: increases hardenability, and provides high temperature precipitation hardening (through the carbide WC), and provides solid solution hardening.

(ii) The *critical diameter* D_o for a steel is the diameter of a long bar, quenched in a given medium, which forms 50% martensite at its centre.

Comparing the dimensions of the component with the critical diameters of the steels, a 20mm bar will cool more rapidly than the component, but 40, 150 or 220mm will all cool more slowly at their centres than the component – so any of these will give more than 50% martensite. Oil cooling is more severe than air, which gives a greater risk of quench cracking (particularly in a tool steel, with a stress concentration at the corner of the section change). Hence the optimum choice is the second steel with air cooling (critical diameter 40mm).

Tempering at an intermediate temperature is required after air cooling (following austenitisation solution treatment), to give precipitation hardening with alloy carbides (and iron carbide), and to restore the fracture toughness to an acceptable value.

(d) Electroplating may lead to hydrogen embrittlement (from atomic hydrogen diffusing in from the electrolyte). High strength alloy steel is particularly vulnerable, and the sharp corner may initiate cracking due to residual stresses from the heat treatment (for which air cooling is again the better choice).

Precautions: reduce the stress-concentration at the corner, if possible; heat treat to remove the hydrogen; use a lower strength alloy, if possible.

(Q3 Powder processing / heat treatment of steels / failure analysis: average number of attempts, average mark.
Few very good answers – a hybrid question on steels, powders and failure with many students unprepared for one aspect, usually powders – part (b) was mostly poorly done or omitted, with many conserving volume and scaling the size in 3D, when it is stated to be uniaxial compaction; in (c,i) many omitted hardenability, which is one of the most important factors in tool steels; in (c,ii) there were few estimates of the equivalent diameter of the part, for comparison with the critical diameters – and a minority that had still not grasped the distinction between the cooling rate in a part, and the critical cooling rate of an alloy.)

4. (a) (i,ii)
Power tool housing: polyester + short glass fibres
- stiffness, strength, impact resistance all needed, so choose higher performance reinforced thermosetting polymer
- housing needs to be reasonably heat-resistant, as internal motor/cooling fins etc get fairly hot (all the options are good thermal and electrical insulators)

- housing is a two-part shell, with integral features for stiffening, assembly/joining, and mounting internal parts: so use compression moulding using a pre-form panel of polyester-short glass fibre; may also be possible to injection mould, if viscosity not too high with 20% fibre content, and the shape details are simple.
- glass fibres stiffen polymer, and moulding aligns fibres in-plane; thermosetting polymer stiffened by cross-linking

Carbonated drink bottle: PET
- PET amorphous so transparent (and easily coloured); also food-safe, and resistant to diffusion of CO_2 (determining loss of pressure and shelf-life)
- stretch blow moulding: thread already moulded into injection moulded parison
- efficient for transport: parisons shipped to bottling plant, which are formed before filling
- large strain by inflation aligns molecules in the wall for stiffness and strength (more strain in hoop direction, in which stress due to internal pressure is double)

Toy gearwheels: nylon
- stiff, relatively hard, low friction polymer: good for gears
- injection moulding: low-cost route to make small intricate shapes with sufficient precision
- stiffness enhanced if cooling rate slow enough to develop crystallinity

Food packaging: LDPE
- LDPE: transparent and cheap, food-safe; recyclable
- blow moulding: inflates polymer to very thin film, minimising material usage
- highest stiffness and strength in-plane, by large stretching of the film

(b) Types of damage:
- environmental degradation by wicking of moisture: delamination and loss of stiffness: affects GFRP, not CFRP
- leaching (surface dissolution) of glass fibres, degrading properties
- matrix swelling by absorption of water, degrading properties or stresses causing cracking
- interply stresses from cooling after forming due to differential contraction (greater in CFRP), leading to delamination
- microbuckling in compression (especially CFRP)
- sub-critical transverse ply cracking and delamination, increased by cyclic loading (leading to loss of stiffness, strength)

(Q4 Polymer material/process selection / failure of fibre composites: low number of attempts, above average mark.

Unpopular question that was mostly done well by those that selected it. Several chose the same polymer more than once, in spite of the question stating they were all different. There was some confusion over the distinction between molecular alignment and crystallinity.)