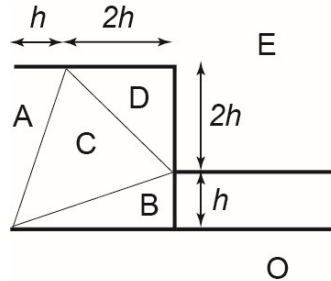


3C1 Materials Processing and Design, and 3P1 Materials into Products – Solutions

Q1. (a) High temperature will reduce the material yield strength, reducing the forging load and potentially speeding up the process. Having to pre-heat the material will not slow the process down as this can be done in parallel, but comes at a cost (with additional CO₂ emissions). It will be more difficult to lubricate at temperature – higher friction will increase the load, but it also drives inward flow and promotes effective filling of the cavity. Steel will oxidise at temperature meaning surfaces are likely to need machining to meet the target dimensions and surface finish, again adding cost. Flash removal will be required regardless of the temperature. Dynamic recrystallisation in steel at high temperature will give a lower final strength with a different grain size. This is a relatively minor issue in steels, where strength is determined primarily by the C and alloy content, with potential further heat treatment such as quench/temper for steels other than mild steel.

(b) First find lengths of the interfaces (see Table):



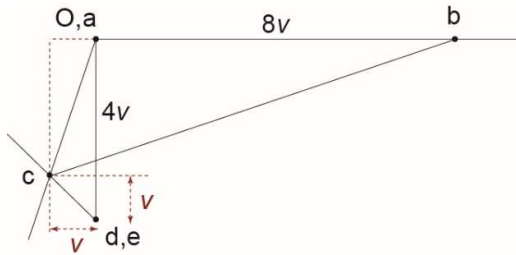
Velocity diagrams: note that D is a dead metal zone, so moves at the same velocity as the upper die E.

A stationary

B stationary

Note:

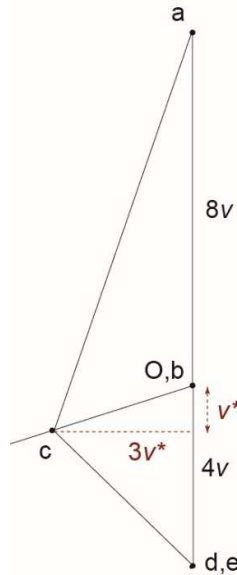
- B moves horizontally, at twice the speed as the upper die, to conserve volume;
- vertical and horizontal components of **ac** in ratio 3:1, and **cd** in ratio 1:1. Hence horizontal component of **c** = 1 (see construction lines).



Note:

- vertical and horizontal components of **bc** in ratio 1:3, so let these be v^* and $3v^*$. Hence vertical component of **cd** also $3v^*$ (see construction lines).

- **bd** = $4v = 3v^* + v^*$, so $v^* = v$



Relative velocities and product with interface lengths, for RH half of the forging:

	Length ($x h$)	A stationary		B stationary	
		Δv ($x v$)	$L \Delta v$ ($x hv$)	Δv ($x v$)	$L \Delta v$ ($x hv$)
AC	$\sqrt{10}$	$\sqrt{10}$	10	$3\sqrt{10}$	30
BC	$\sqrt{10}$	$3\sqrt{10}$	30	$\sqrt{10}$	10
CD	$2\sqrt{2}$	$\sqrt{2}$	4	$3\sqrt{2}$	12
OB	3	8	24	0	0

Power in (per unit depth) = $F \times 4v = 4Fv$

Frictionless case: neglect OB. In all cases, internal dissipation $\times 2$, due to symmetry.

Zero friction, A stationary: $4Fv = 2 k hv (10+30+4)$, hence $F = 22kh$

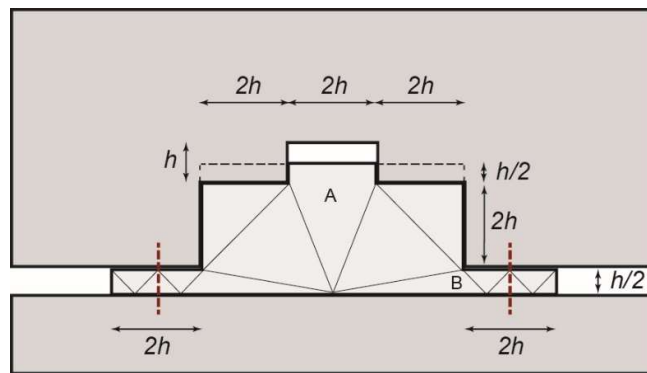
Sticking friction, A stationary: $4Fv = 2 k hv (10+30+4+24)$, hence $F = 34kh$

Zero and sticking friction, B stationary: $4Fv = 2 k hv (30+10+12)$, hence $F = 26kh$

For low friction, the first mechanism is expected, with formation of flash on both sides. In theory the cavity will just fill when the top die has moved a distance h , but this requires the flash to reach zero thickness, and even a small amount of friction will lead to a friction hill over the flash, rising steeply with aspect ratio – so this mechanism will stop operating well before the dies have closed. However. As this then drives *inward* flow, and the cavity should fill – see below, when gap = $h/2$).

For high friction, the second mechanism is expected, with inward flow driving material into the cavity, which will fill completely with little flash formation (in the limit of zero flash being formed, the die will fill when it has moved $h/2$, by conservation of volume).

(c) Once a flash forms (with or without friction), slip bands are required to enable the flash to extend laterally, and get thinner. As the aspect ratio rises, in the presence of friction the pressure rises and more energy is dissipated in the flash. It is likely that (stationary) neutral planes form in the flash (shown dashed in fig.), and the flow reverses in the inner part of the flash and block B. This pushes block A upwards into the cavity, and it will fill comfortably under a degree of internal pressure, giving good dimensional accuracy.



Assessor comments:

(a) Straightforward short opening question, mostly well-answered, with the usual minority muddling contexts – e.g. referring to issues in aluminium extrusion (such as surface melting due to deformation heating) in the context of steel forging.

(b,c) Wide distribution of marks, with a good minority knowing exactly what they were doing. Even with the correct velocity diagrams, there were many errors in the analysis, or attempts to measure directly from small poor diagrams – only one student drew a large scale diagram on graph paper. Most spent a lot of time doing unnecessary trig, without recognising that the relative velocities could be found via some simple ratios and Pythagoras (i.e. everything in surds, giving exact integers for $L \Delta v$ terms). Some students chose the lower of the two bounds for a single mechanism, comparing low and high friction cases, rather than choosing between mechanisms for each separate friction case.

Q2. (a) (i) Gravity die casting: relies on pouring melt into the mould, so molten polyester is too viscous to flow, without pressure – particularly when glass-filled (or to flow through a pre-positioned mat of fibres in the mould, without disrupting the fibre alignment). Low density also gives low hydrostatic pressure to drive flow into the mould. Economically the mould would be similar for a viable polymer process (such as shell moulding, or wet hand/spray layup), so this isn't an issue – though vacuum bagging would be more costly.

(ii) Investment casting: very thin sections – hard to fill with liquid metal, and hard to make in wax (especially tapered, sharp edge). Even with multiple parts per mould, it is a slow batch process for a product like razor blades, produced in large quantities. Also require high strength (especially sharp edge) – need wrought process and alloy, rather than cast. Use a rolled thin strip (probably heat treated), stamp to shape, and grind the sharp edge; surface treat for hardness to keep the cutting edge, resist corrosion, and reduce friction.

(iii) Hot isostatic pressing: used for technical ceramics requiring low porosity with good mechanical properties, mostly in complex axisymmetric shapes (with only simple interior hollow profiles being possible), using radial compaction within a thin metal container. The high temperature, vacuum equipment is expensive, requiring high value applications, or high production runs (the cycle time can be reasonably fast). Teapots are low cost, hollow 3D shapes made from porous pottery, often made in modest batch sizes, requiring a low cost shaping technique: slip casting – low cost ceramic two-part moulds suitable for teapot shape, wall thickness reasonably uniform but not critical. Slow overall cycle time, but slip casting is rapid – it is the drying, firing and glazing that require time and storage space.

(iv) Induction hardening for wear resistance (could be either for through-thickness quenching and tempering, or for surface transformation hardening): the part is quite large to use a custom induction coil for heating, but in any case mild steel has too little carbon to quench to martensite. It is a slow batch process to use for large numbers of blades. After stamping out the shape from rolled sheet and grinding the cutting edge, use a low cost surface hardening technique for the whole surface, which does not affect the shape cutting edges (e.g. carburising, after which could also quench to give a martensitic layer; or use a thin coat spraying/dipping technique), to improve resistance to wear and corrosion.

(v) Thermal spraying (e.g. high velocity oxy fuel), for wear resistance: spray molten droplets of hard alloy onto surface forming 'splats' in layers greater than 0.1mm thick; poor control of coated region, and surface finish. Sustained heating of surface close to the melting point may over-temper the underlying material (though cutting tools run hot anyway in service, and are hardened by stable alloy carbides). Cutting tools are high precision shapes with sharp edges – dimensions/shape must be unchanged, or coatings very thin. Tool steel already hardened, so laser transformation hardening is viable, and fast (though spiral profile requires complex set-up and control of laser (traverse spot while rotating part). A better alternative is PVD to deposit TiN for wear resistance.

(b) (i) Discolouration and cracking (due to embrittlement with age) indicate UV degradation of the nylon.

(ii) Injection moulding:

The part has re-entrant details that make removal from a mould difficult – parting planes can expose the part with attached to a mould part filling the internal cavity, but releasing the part requires either a large elastic strain, or sliding it axially off the mould. It may be necessary to make multiple smaller lengths (e.g. 5-10cm) to build up the 0.5m length, enabling the use of a smaller mould (assuming the sliding mechanism works OK with un-connected butt joints between the parts). Complex mould likely to be a very expensive option for one replacement part. Surface finish and precision good however.

Additive manufacturing:

The part geometry can be made by a powder bed or jetting process in nylon – built up from the top face placed on the base-plate, the overhanging semi-circular part may be OK (but if not this can be built first and the part rotated to build up the other two sides). For a one-off part at low cost, AM is ideal. Quite a long part for AM – depends on equipment available – but as for moulding it may be acceptable to use several shorter sections (if the slider does not catch on the joints). Surface finish rougher than moulded part, but achieving a secure fit round the Al support does not require a very good finish – only the sliding top surface: obtain a good finish by building this face on the bottom plate, or light grinding/polishing this face afterwards.

Assessor's comments:

(a,b) This question required discussion of the suitability of processes to parts made in specific materials, with guidance on the considerations to cover. There were few very good answers, with many students just brain-dumping everything they could say about a process, without reference to how the information was relevant to the problem in hand. Some students made good use of the Databook process attribute charts to comment on technical or economic limitations. There were also some strange misconceptions, such as HIPing being unsuitable for ceramics as they would fracture under pressure. Detailed knowledge of AM was evident in many students, concerning practicalities of optimising the build geometry and finish, with a few giving excellent ideas for redesigning the part to facilitate processing by both of the manufacturing techniques.

Q3. (a) (i) In casting, the underlying physical basis of grain formation is the number of solid nuclei formed, and the distance that the solid-liquid interface moves before impingement on another interface and completion of solidification. Rapid cooling by the mould creates a chill zone with fine grains at the surface, after which an evolving thermal gradient becomes established across the solid-liquid interface. Partition of solute between liquidus and solidus leads to enrichment of solute ahead of the interface (with gases dissolved in liquids being largely expelled completely on final solidification). The grain structure and size determines the *length scale* over which segregation and porosity occur – macrosegregation and macroporosity in the mid-section of the casting is caused by columnar growth that gives grains extending across half the thickness. Columnar growth of large grains is favoured by steeper thermal gradients; dendritic equiaxed growth occurs if the gradient leads to constitutional supercooling ahead of the interface. This leads to microsegregation and microporosity, with both being trapped in solidifying pockets of liquid throughout the casting. The temperature gradient is determined by the choice of mould material, and the initial pour temperature of the melt (also the size and shape of the casting – but these are assumed fixed for a given cast ingot).

This can be modified by the addition of *inoculants* – solid particles that promote heterogeneous nucleation in the central region, reducing the grain size and severity of segregation and porosity. The choice of eutectic compositions avoids the formation of primary Al-rich grains – the mechanical properties of eutectics being dominated by the two-phase microstructure, rather than grain-size – so segregation is minimal, and microporosity promoted. (While poisoning is a further addition that refines the size and shape of eutectic Si, this is primarily for mechanical properties, and does not influence segregation or macroporosity).

(ii) Low carbon steels contain a low amount of carbon, which forms a small volume fraction of iron carbide, within grains of pearlite (and a limited amount of solid solution in ferrite). Steels dynamically recrystallise during hot rolling and continue to recrystallise statically during annealing, so the final state is soft with no work hardening. The strength and formability are therefore determined by the intrinsic strength of iron, and the grain size, which gives some grain boundary hardening. The grain size is sensitive to many process variables in the hot rolling and annealing: prior grain size (from previous processing steps), rolling temperature, strain-rate and strain, and annealing temperature and time. A minimum strain and temperature is needed to trigger recrystallisation.

(iii) Structural carbon steels should have low hardenability, to avoid the formation of brittle martensite with low fracture toughness. The main role of grain size in welding is the austenite grain size in the HAZ (and weld metal) during welding, as this affects the hardenability – both via the number of nuclei for forming ferrite/pearlite/bainite on cooling, and by the growth distance for these phases to complete the transformation from austenite. Large austenite grains are more hardenable, and therefore more susceptible to martensite formation and low fracture toughness – so initially fine-grained steel helps. Grain growth in the austenite is promoted by slower thermal cycles (governed primarily by choice of power and speed, notably the ratio q/v , for a given weld geometry). The cooling rate is governed by the same parameters, and operates in the opposite direction – higher heat input increases the austenite grain size, but reduces the cooling rate, so there is a trade-off, and the worst cases may be at intermediate q/v .

The outcome may be manipulated by microalloying – addition of Ti, Nb to form carbides that are stable at high temperature in the HAZ, and pin the austenite grain boundaries, maintaining low hardenability.

(b) (i) A higher fraction of intermetallics/dispersoids in Al alloys may influence recrystallisation in particular, by particle-stimulated nucleation. So the final recrystallised grain size will be smaller, which will have a modest effect on strength. Containing more particles is likely to reduce the ductility and make the material less formable (recalling ductile fracture in IA Materials; the texture will also be more random, and this will affect formability – not covered in lectures).

(ii) Dispersoids are most important in extrusion/ageing through quench sensitivity – the unwanted coarse precipitation of equilibrium phases that nucleate on dispersoids during the quench. This removes solute from the super-saturated solid solution after quenching, reducing the peak strength that can be produced by age hardening.

(c) Wrought alloys all contain Mg plus other elements that give solid solution strength (Mn) or age hardening (Si, Cu, Zn), typically up to 5% maximum in total (with much lower Si content) – always below the maximum solubility as a single phase in aluminium. Casting alloys contain primarily Si, around the eutectic composition (12%). Hence adding a lot of old castings to recycled wrought alloys takes the composition way outside acceptable limits for Si content – these limits are essential to maintain high productivity in extrusion of complex shapes with low scrap-rates, as well as providing the target age hardening response in heat-treatable alloys, and in all wrought alloys avoiding the lower toughness of casting alloys, which is a consequence of their microstructure containing Si as a brittle single phase).

Assessor's comments:

(a,b,c) A fairly synoptic question, drawing on diverse metallurgical content from around the course. A small minority produced excellent answers and clearly understood the underlying science. The majority were (to varying degrees) muddled and imprecise, many using technical terms almost at random from multiple material/process contexts. Generous marking was needed, often picking out correct points sparsely scattered amidst pages of irrelevant half-baked regurgitation of the notes.

Q4. (a) (i) Mechanical: sub-divided into Fasteners (addition of another part to form the joint – screws, nails, rivets, clips), and Deformation (plastic deformation of sheet parts, e.g. crimping).

Welding: plasticity and/or heat at the joint interface between the materials, subdivided into:

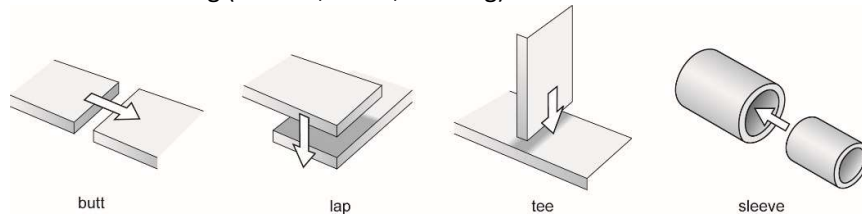
Cold (low/ambient temperatures – using plasticity) – e.g. cold charring

Hot (plastic creep regime, $> 0.5 T_m$) – e.g. friction welding.

Fusion (local melting and solidification of the materials, $> T_m$, sometimes with additional filler material making up most of the molten weld metal) – e.g. resistance, MIG/TIG, laser.

Solid-state: no deformation or melting of the parts, with an adherent interlayer solidifying or setting between them sub-divided into Adhesives (viscous curable polymer interlayer such as epoxy), and Brazing/Soldering (low melting point molten metal interlayer – the distinction between them being the operation temperature).

(b) After material compatibility, the main primary considerations are: joint geometry (butt, lap, tee, sleeve – see figure) and mode of loading (tension, shear, bending).



Example interaction: adhesives require lap joints, but these can still only be loaded in shear, but not bending. (Recall from IA Structural Design: “don’t use single rivets in shear” - as the sheets twist, and the rivets can pop out, i.e. need to use bolts).

(c) (i) MDPE gas pipes, in a trench: use hot-plate (fusion) welding, suitable for butt joints between thick-walled thermoplastic (tensile/bending loads moderate, from internal gas pressure and handling pipes during installation). Equipment needs to be compact and portable, including the power supply, for use on-site in an outdoor environment, frequently moved from location to location. Must be gas-tight (avoid leakage from the inside), and water-tight (avoid leakage from the outside).

(ii) Gold interconnects in printed circuits: ultrasonic welding. Material compatibility – soft pure metal for small-scale plastic deformation (and lack of oxide helps with metal-metal bonding), small lap joint. Electrical conductivity of joint must be as high as possible. (Soldering OK but less suitable, as adds a lower conductivity interlayer, and requires higher temperature and heat input, potentially damaging electronics).

(iii) Tubular steel climbing frame: nuts and bolts – often “wing nuts” – with sleeve joints between tubes (or one tube end flattened and shaped into a semi-circle to slot onto the other tube). Tubes with profiled ends may also form sleeve joints to mechanically interlock (like tent poles). The main secondary criteria are the need to disassemble (to change height, or re-configure with additional sections for accessories), good strength and corrosion resistance and no sharp edges – child safety is critical.

(d) (i) Crevice corrosion with trapped water in the gap between lamp-post and concrete. Oxygen is quickly used up, giving differential aeration – the submerged steel becomes anodic with respect to the exposed part of the post and corrosion below the concrete surface is accelerated. Dog urine acidity makes the situation worse!

(ii) Hydrogen-assisted stress corrosion cracking: thread root acts as a stress concentration to magnify already high cyclic stresses on the bolt, initiating a fatigue crack through the Zn and hardened carburised layer into the underlying steel. The crack is sitting in a corrosive wet environment – wet corrosion of the Zn leads to release of H^+ ions in the cathodic process, with rapid diffusion to the fatigue crack tip accelerating crack growth and causing early failure by fracture.

(iii) Weld decay (sensitisation): stainless steels (austenitic) contain very low carbon, but at the elevated temperatures in welding, C reacts with the Cr to form carbides, but only on the grain boundaries (where diffusion and nucleation are enhanced). The Cr-depleted boundaries are then anodic with respect to the bulk of the grains, giving localised corrosive attack of the boundaries. Grains can fall out of the surface (pitting), and cracks can penetrate along boundaries into the material.

(iv) Microbial corrosion: bacteria in sewage sludge that thrive in low oxygen environments. These can excrete acidic sulphide ions, reducing the pH, and accelerating anodic dissolution (local galvanic cells) and stress corrosion cracking, leading to pitting and cracking, and eventual failure.

Assessor's comments:

(a,b,c) The most straightforward and best answered of the descriptive questions, though still with a long tail of weak guesswork. Many guessed design requirements for joining based solely only on past paper questions, rather than the lecture notes, and went into great detail on corrosion problems and how to re-design the joints – none of which was asked for. Some intriguing misconceptions, e.g. don't use fusion processes for gas pipes or there will be a fire!

(d) A high proportion of disappointing answers, showing little knowledge or understanding beyond IB (and in many cases not even that). Many provided possible solutions to the problems – again brain-dumping and answering questions from other past papers, but gaining no credit as this was not asked for in the question.

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