

3C1 Materials processing and design /3P1 Materials into products 2017

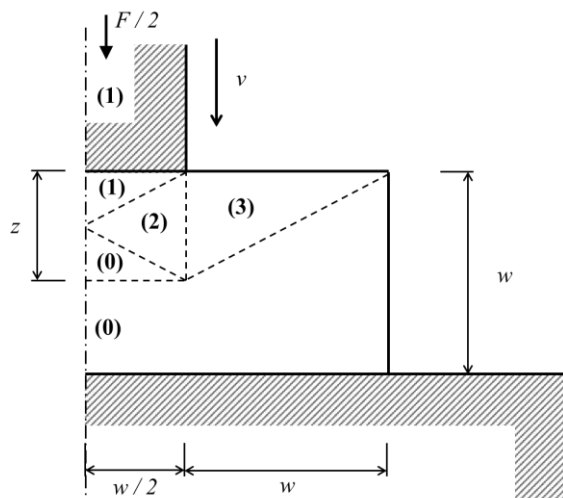
Answers

1. Plane strain forging of a block:

(a) Upper bound method:

(i) The plastically deforming material is assumed to behave as a set of rigid blocks sliding relative to one other, resisted at the interface by the shear yield stress k .

- First, label each block. Note that, for reasons of symmetry, blocks (0) and (1) do not move relative to the undeforming material and the indenter, respectively:

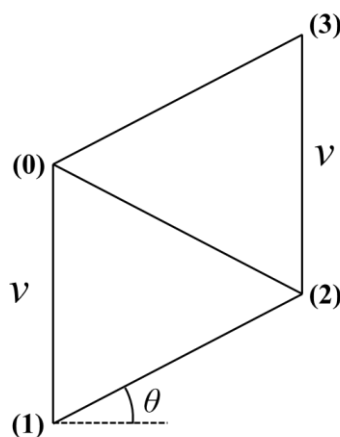


The interface lengths are:

$$L_{03} = 2L_{12} = 2L_{02} = \sqrt{w^2 + z^2}$$

$$L_{23} = z$$

- Next, draw the velocity diagram:



The relative velocities are:

$$v_{01} = v_{23} = v$$

$$v_{03} = v_{02} = v_{12} = \frac{v}{2 \sin \theta}$$

Geometry:

$$\sin \theta = \frac{z}{L_{03}} = \frac{z}{\sqrt{w^2 + z^2}}$$

$$\therefore v_{03} = v_{02} = v_{12} = \frac{v}{2z} \sqrt{w^2 + z^2}$$

- Finally, equate the internal and external work rates. Per unit depth out-of-plane:

$$\frac{F}{2} v = kL_{12}v_{12} + kL_{02}v_{02} + kL_{23}v_{23} + kL_{03}v_{03}$$

$$= k \frac{v}{4z} (w^2 + z^2) + k \frac{v}{4z} (w^2 + z^2) + kzv + k \frac{v}{2z} (w^2 + z^2) = kv \frac{w^2}{z} + 2kvz$$

$$\therefore F = 2kz \left[\left(\frac{w}{z} \right)^2 + 2 \right]$$

(ii) The best upper bound for this assumed mechanism of plastic deformation is found by minimising F with respect to the variable z :

$$\frac{dF}{dz} = 2k \left[-\frac{w^2}{z^2} + 2 \right] = 0, \quad \therefore z = \frac{w}{\sqrt{2}} = 0.71w$$

Substitute back into the expression for F to get the best upper bound:

$$F = 2k \frac{w}{\sqrt{2}} \left[\left(\frac{\sqrt{2}w}{w} \right)^2 + 2 \right] = 4\sqrt{2}kw = 5.66kw$$

Trying some other values confirms that this is a minimum:

$$z = 0, F = \infty$$

$$z = 0.5w, F = 2k \left(\frac{w}{2} \right) \left[\left(\frac{2w}{w} \right)^2 + 2 \right] = 6kw$$

$$z = w, F = 2kw \left[\left(\frac{w}{w} \right)^2 + 2 \right] = 6kw$$

(b) Equilibrium method:

(i) Method involves

- set up force balance across the volume element shaded in Fig 1c
- pressure p acts on top and bottom faces (and p is function of x)
- normal stress in x direction changes as we move across the block, with b.c. zero at $x = w/2$
- assume sticking friction at top and bottom faces, so shear stress on them = k
- apply yield criterion to element to produce a differential equation in p
- then integrate to get p as a function of x

(ii) The forging force (per unit depth) is found by integrating the pressure:

$$\frac{F}{2} = \int_0^{w/2} p dx = \int_0^{w/2} k \left(3 - 2 \frac{x}{w} \right) dx = k \left[3x - \frac{x^2}{w} \right]_0^{w/2} = \frac{5}{4} kw$$

$$\therefore F = 2.5kw$$

(c) The forging load predicted by the equilibrium method is lower than the best upper bound calculated in part (a). This indicates that this upper bound can be improved upon. This can be achieved by proposing alternative assumed mechanisms of plastic deformation, that more accurately reflect the real material behaviour. Possible approaches to try include:

- Under the indenter: splitting triangles (1) and (0), to allow material in contact with the indenter and the undeforming material to flow in the horizontal direction (this horizontal flow occurs in the equilibrium analysis).
- To the right of the indenter: splitting triangle (3), to enable the plastic flow in this area to be more concentrated near to the indenter.

2. (a) The mould filling rate depends on the physics of metal flow through the cavity within the mould, cooling as it does so (with the target of filling the mould before the onset of solidification). The following parameters influence the filling rate:

- alloy:

- determines viscosity and hence flow rate through channels;
- thermal properties affect conduction rate (hence onset of solidification);
- composition determines liquidus and solidus temperatures (from phase diagram), and hence onset of solidification (increase in viscosity, and narrowing of channels for flow)
- density affects the pressure difference and hence flow rate in gravity casting.

- process design and variables:

- number and location of ingates (govern flow distances);
- pour temperature and mould material + hence thermal properties (control heat flow and cooling rate of melt and hence onset of solidification):
- whether filling is under gravity or pressure (affecting viscous drag through channel of given size and roughness of mould walls);

- part design:

- size and shape of casting – particularly the aspect ratio of channels through which the liquid metal flows (affecting flow velocity), but also affecting cooling rate (by conduction into mould).

[full marks for 5 of these bullet points]

(b) (i) V = volume of part, A = surface area. Heat diffusion through the casting to the surface, which will control the solidification time, will vary according to $x \approx \sqrt{(kt)}$ where k is thermal diffusivity and x is half the shortest dimension of the part. x will scale with V/A , and hence the solidification time will vary as $(V/A)^2$.

(ii) We can approximate a thin-walled shape as a flat plate, for which $V = d \times \text{plate area}$. where d is the thickness. The surface area A (remembering that heat is lost from both sides of the plate) is therefore $2V/d$.

From Chvorinov's rule, $t = C (d/2)^2$ where $d = 4$ mm.

Hence $t = 0.65 \times (4/2)^2 = 2.6$ s.

(c) Parting plane should be at the level of the top of the pot, though in practice would be cast upside down. This is because of the tapered shape, allowing the pattern to be released from the mould (not the casting itself, as the sand mould is broken up).

One of the ingates should just use the handle attachment feature, as this is formed from already a wider channel in the mould entering at an appropriate place near the rim (located at the bottom when upside down), and it needs cutting to length after casting in any case.

(d) Various types of defects that could form (one of each required):

(i) mould filling:

- mis-run: incomplete filling of part of section – increase pour temperature or re-design ingates;
- cold shut: incomplete mixing of two flows from opposing directions – ditto.
- mould damage (and entrapped debris from mould): due to mould erosion near ingate – solve by reducing metal flow rate;
- turbulence defects (entrapped bubbles and excess oxide) - ditto.

(ii) solidification:

- porosity from dissolved gases released on solidification but unable to escape (improve by vacuum degassing the melt – expensive for a cooking pot – so promote fine microstructure and trapped microporosity, or alloy with a “killing” element to take up dissolved oxygen in solid form);
- shrinkage defects (loss of dimensional accuracy as casting solidifies and contracts) – solve by good design of runners and risers to solidify after the pot, providing fresh supply of liquid to take up the contraction volume.

(e) 3.5 wt% C gives a near-eutectic cast iron, hence (i) retains good fluidity (zero freezing range); (ii) more economic (lower temperature for full melt, so less energy input and higher productivity); (also relatively low shrinkage between liquid and solid, giving better tolerance);

0.5 wt% Mg is a poisoning element, which spheroidises the graphite into “nodules”, improving the strength and toughness of the cast alloy.

(f) Enamelling protects the cast iron from corrosion, gives a smooth finish (easier to clean, and with an aesthetic shine), and enables colouring and branding. Different colours inside and out are possible. Disadvantages are the additional complexity and cost of another process step (more complex for two colours); the brittleness of the enamel (glass) can lead to chipping damage in use.

3. (a) Alloy A is hardened by work hardening (increased dislocation density); Alloy B has no work hardening (annealed) but the alloy content is higher giving solid solution hardening (which could be similar to the work hardening in alloy A); Alloy C is precipitation hardened, which is the most effective mechanism – but it is naturally aged, which gives a more modest hardening response, and the alloying content is modest (so could be similar strength to A and B).

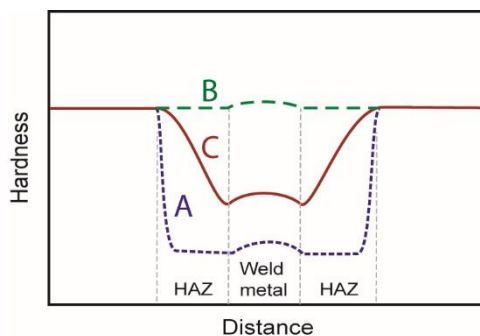
(b) Annealing after hot rolling leads to *static recrystallisation*. As an Al alloy it will have already undergone dynamic recovery during hot rolling, leaving a sub-grain microstructure within the grains. Selected large subgrains act as nuclei that grow into new grains of low dislocation density.

The main microstructural features produced by recrystallization are the grain size, and the fraction recrystallized (if incomplete).

- (i) The strain during rolling must exceed some minimum level (depending on the rolling temperature) to trigger recrystallization at all; beyond this the grain size rapidly peaks with increasing strain, then progressively falls (as the stored energy increases, and the probability of forming critical subgrains increases);
- (ii) second phase particles and dispersoids act as nucleation sites (PSN: ‘particle stimulated nucleation’). The number per unit volume determines the probability of their producing a nucleus, so the higher the number of particles, the finer the grain size.

(c) (i) TIG welding uses an electrical arc discharge between the workpiece and tip of a (non-consumable) tungsten electrode as the source of heat. Filler material is supplied as wire or rod into the arc/melt pool. The melt pool is shielded by inert gas (usually argon) to prevent oxidation.

(ii) Hardness profiles straight after welding:



(iii) A: recrystallization removes the work hardening, and the residual strength is low (as only comes from the low alloy content in solid solution).

B: welding has no effect on hardness – solid solution strength remains unchanged, so no heat-affected zone.

C: precipitates undergo “reversion” and re-dissolve, giving a drop in hardness (progressively more across HAZ towards weld centre)

In all cases, the weld metal will only be hardened by solid solution hardening immediately after welding.

(iv) One week later, alloy C will have naturally aged, with dissolved solute going back into fine scale precipitation and restoring the hardness to more or less the initial level prior to welding. Hence alloys B and C will both have similar strength but A will be weaker.

(d) Other factors to consider in finalizing alloy, design and process.

- for fusion welding, the key operating variables are power and speed, determining the thermal history (and thus size of the HAZ, and the loss of strength), and also influencing residual stress and distortion during assembly. These variables will also affect the production rate and cost.
- using alternative thermal joining processes (e.g. friction stir welding) would change the size of HAZ and hardness profile, and residual stress etc.
- using adhesives or mechanical joints would avoid loss of hardness and residual stress, but would require changes in joint geometry to give overlaps between the sheets, instead of a butt joint. Changing process also has production rate and cost implications.
- as choice of process affects strength differently in each alloy, the choice of process will influence which alloy is selected to meet the loading requirements (as well as aspects such as corrosion resistance). This will also influence the production cost of the trailer.

4. Alumina.

(a) Powder processing.

Material in fine powder form (particle size generally ranging from 50 to 500 μm) is pressed into a mould to produce the required shape by cold compaction, using high pressure (100-150MPa). A rigid die may be used with uniaxial pressing, or a flexible mould may be used with cold isostatic pressing. The cold compact is then heated to sinter it, with or without pressure: the particles bond together by interdiffusion to form components. For pressureless sintering the compact will be held at $0.7-0.9T_M$ for several hours.

(b) For uniaxial pressing into a rigid mould the compact will have a range of densities, resulting mainly from friction between the powder and the die. When the compact is sintered, these regions shrink by different amounts. The high strength and brittle nature of the ceramic means that there is little scope for relaxing the stresses, so components contain internal elastic stresses. This may lead to cracking. The high elastic modulus means that there is generally not much distortion but there may be some.

The homogeneity of the cold compact produced by uniaxial pressing may be improved by increasing lubrication between powder and die, and by die/punch design (achieving more uniform compaction ratios for different thickness regions by using multiple punches; punches moving from both top and bottom). Better homogeneity of the compact but dies and press are more costly.

(c) Isostatic pressing would give more uniform distribution of density in the green compact but at the penalty of reduced dimensional accuracy.

HIPing could be used (powder canned in metal container; heated to $0.8T_M$ under high gas pressure, typically 10MPa). Very low final porosity; homogeneous component; short sintering time (minutes); no grain growth so improved mechanical properties. Disadvantages: expensive and lower dimensional accuracy.

The component thickness is somewhat big for Powder Injection Moulding (maximum 5 mm, limited by debinding stage and the need for volatiles to be removed evenly from the compact and without slowing down the process excessively), but the process might be possible. Process: ceramic powder mixed with 50% polymer binder and injection moulded; polymer removed by gentle prolonged heating (debinding); brown compact sintered. High dimensional accuracy; very low porosity; good mechanical properties. Favoured for high volumes and high-quality parts. 3D printing processes are also possible (based on deposition of ceramic particle slurry).

PE

(a) Molten polymer is forced into a shaped metal mould at high speed and pressure using a screw extruder. The molten polymer accumulates in a chamber in front of the screw, and once the chamber is full is the whole charge ejected into the mould cavity. It cools and solidifies rapidly, and the mould is then opened to release the article. Very short cycle times can be achieved (~seconds – but determined by the cooling time).

(b) The variable thickness will result in a range of cooling rates. PE will crystallise, and the amount of crystallization increases as the cooling rate decreases. Thick sections therefore have higher crystallinity than thin sections. Crystalline regions have higher density and so shrink more than amorphous regions. The component will distort to accommodate the internal stresses, leading to sink marks and other distortion affecting dimensional accuracy, often out-of-plane.

The problem can be reduced by control of injection moulding parameters: cooling the mould to reduce the amount of crystallinity even in the thicker sections; increasing the injection pressure to pack more polymer into the mould, so providing some compensation against shrinkage; increasing hold-on time - keeping high pressure on the polymer as it solidifies in the mould, allowing molten polymer to enter the mould during solidification. Some of these measures will slightly decrease the cycle time, so essentially increasing the process cost, but the effect is small.

(c) Thermoforming might be used. Starting from a polymer sheet, the material heated to above T_g and then pressed into a mould using a vacuum or moving dies. Disadvantages: achieving the variable section thickness may be compromised; process likely to be slower than injection moulding so suitable only for lower production volumes. Machining from extruded bar is also possible, depending on the complexity of shape, accuracy required, and production volume.

Assessor's comments on student answers

Q 1: Analysis of forging

(a) Most candidates knew what they had to do, but success was blighted for some by an inability to draw the velocity diagram, use Pythagoras to deduce lengths, or manipulate (and eventually differentiate) simple algebraic expressions.

(b) Descriptions of the steps involved in the equilibrium method were sketchy in some cases, and several candidates used the wrong upper limit for the integral (using the full width of the block rather than the edge of the upper die.)

(c) There were generally sensible comments on the comparison and on the need for a better deformation pattern in the upper bound model.

Q 2: Casting

An untaxing question, generally well done.

(b) The physical basis for Chvorinov's equation was understood by most, but errors were made in the simple calculation by candidates who tried to overcomplicate the problem by inventing dimensions for the casting, and by those who failed to realise that heat would be lost from both sides of the thin section.

(e) There was considerable misunderstanding of the role of magnesium in grey cast iron, with several confusing it with that of manganese in steels. Most understood the benefits of the composition being close to the eutectic.

Q 3: Aluminium alloys

The least popular question with the lowest average mark, demanding an understanding of aluminium alloys that some candidates evidently did not possess.

(a) While most recognised work-hardening in A and precipitation hardening in C, fewer seemed to be aware of solid solution strengthening in B and ascribed its strength to precipitation hardening instead.

(b) There were some weak answers on recrystallization and a general lack of awareness that a critical strain is needed for it to occur.

(c) While most were aware of the principles of TIG welding there were some inventive suggestions from others, including both tungsten and titanium as the weld material. Sketches of the hardness profiles across the weld region were in many cases very poor and not based on an understanding of the mechanisms involved, with some even showing an increase in hardness in the weld region over that of the parent material. Very few appeared to understand that the weld itself had been melted and resolidified rather than simply heat-treated. A few students wrote about heat-treatment of steels.

Q4: Ceramic and polymer processing

The most popular question, generally quite well done.

(a) Most gave reasonably competent accounts of the processes of pressing/sintering and injection moulding.

(b) The origins of inhomogeneity in ceramic processing were less clear, with many focusing on particle size and shape. Most candidates gave good accounts of the effects of cooling rate on crystallisation in the polymer, and the consequences of different cooling rates in the product.

(c) Some imaginative answers were completely unrealistic and suggested a poor general understanding of the principles and limitations of certain manufacturing processes. Quite a few candidates did not appreciate that melt-processing could not be used for alumina.