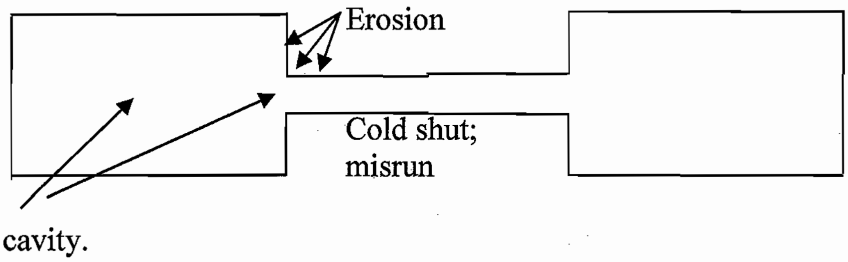
MET1 Paper P4A 2007
(Module 3C1)
Materials Processing and Design
CRIB (C. Barlow)

1 (a) (Answers should include a diagram). Two-part mould, with *pattern* probably divided horizontally into two equal parts. Bottom part laid upside down in *drag*, covered in *green sand* and tamped down. Mould then inverted and pattern removed. Top part of pattern similarly laid in *cope*, together with patterns which will form the following: *pouring basin, sprues, vents, risers and feeder heads, runners, in-gates.* Sand added and consolidated as before. Patterns removed (before and after inverting mould, as required), and features which were not created using patterns carved in. Cope inverted and placed on drag; complete mould bolted together.
Metal is poured into the pouring basin, and enters the mould via sprue, runner and in-gate. Air escapes through vents, positioned at high points in the mould. A riser will be situated so that it fills with molten metal; when metal appear in it, the mould is full. The sprue and riser between them act as reservoirs of molten metal, to allow for contraction of the solid in the mould. Their dimensions should be great enough that metal remains liquid in them long enough to assist with the feeding. Ingates designed to allow metal to flow into mould without turbulence.

(b) This will be a difficult shape to cast:

Abrupt section changes, leading to turbulence
Variable section thickness, leading to differential solidification times
A thin section which will tend to solidify rapidly and cause feeding problems
Two streams of metal which need to combine

There may be surface defects from the sand casting process such as blister, scab if the sand was not made carefully. Casting defects specific to this geometry will be expected as follows:



Erosion: turbulence will tend to cause the sand to wash away.
Solution: reduce the abruptness of the section change by tapering.

Shrinkage cavity: Centre of thick section is last part to solidify; unless molten metal is able to feed in from a feeder head, then the solid metal will be unable to fill the cavity. There may be similar problems at the ends of section B
Solution: Ensure feeder heads are large enough to keep metal molten long enough that sections A have solidified. This means that (Volume/Surface area)^2 for the feeder must exceed that for section A.

Cold shut, misrun: the metal will not easily flow through the thin section since it will tend to solidify; if it fails to fill the section that is a *misrun*. With this geometry, the problems are exacerbated since the metal must be hot enough that the two streams of metal can combine and generate a full-strength bond, rather than leaving a *cold shut*. Reducing or eliminating the problem requires pouring the metal hot enough that it will have the fluidity to get through Section B. If the design permits, the section B could be made thicker.

If the metal were fed into the middle of section B, the possibility of misruns and cold shuts would be eliminated. There would still be the problem of turbulence, as metal flowed from a thin section to a thick one, but with careful pouring this could be reduced. Risers positioned in sections A would need to act as the molten metal reservoirs for the casting.

(c) Porosity is always a problem with castings. Gases come out of solution during solidification, and form bubbles at the last places to solidify on a local scale. So small-scale porosity is found in interdendritic regions, i.e. at grain boundaries.
There may in addition be some particles of sand trapped within the casting if there has been erosion.

(d) Al -20% Si has a semi-solid range of 100°C. This will make shrinkage problems much worse, since liquids have a high thermal contraction coefficient.
The ability of the metal to completely fill the thin section will be much reduced, so cold shuts and misruns will be more common.
On a microscopic scale, there will also be increased porosity in this alloy.

(e) The scale of the microstructure is determined by the solidification time, and is inversely proportional. The mechanical properties of the Al-Si eutectic will be influenced mainly by the size of the brittle silicon platelets (σ_f proportional to defect size$^{-1/2}$) . So the thinnest section B, which solidifies fastest, will have the greatest failure strength.

Strength can be improved by
(i) adding modifier to the alloy: 1% sodium will poison the growth of the Si flakes, reducing their size and causing them to be more rounded (reduced stress concentration).
(ii) removing porosity post-casting by HIPing.

Examiner's comment: Almost everyone showed metal pouring directly into Section A from the top, without use of runners; many people also omitted to include any risers. Some of these errors were picked up by 'improvements' in part (b).
A number of people conflated sand casting and investment casting.
There was a regular stream of mentions of polymer processing in various contexts.
Part (e) was very badly answered. There was much talk of equiaxed and columnar growth, but few people remembered the significance of cooling rate on the scale of the eutectic silicon needles: being brittle they have a large influence on the failure strength. Very few mentioned property improvement by adding a modifier. A lot of people displayed ignorance by proposing that the net-shape cast component be recrystallised (the driving force for recrystallisation being dislocation density, it is of course necessary to plastically deform the material before it will recrystallise...).

2. (a) (i) Uniaxial pressing: Pressing into a mould along a single axis (may be multiple punches, may move from both top and bottom). Compacts a powder into a simple shape, generally non-uniformly. Creates the rough shape for the mirror.
Cold isostatic pressing: Use fluid or gas pressure to compress powder in a flexible mould. Improves compaction and gives much more uniform density.
Green machining: Machining in the compressed state, before sintering to join particles together. Ribs and otyher features will be added. Green compacts have low strength, so machining forces low. Accuracy influenced by need to sinter afterwards, which involves contraction of up to 20%.
CVD: Chemical reaction at the surface of the article, resulting in thin layer with very high integrity. Provides a hard porosity-free surface which can be polished.
(ii) CIM involves creating a mixture of the powder with high volume of polymer binder and using polymer injection moulding processes to create parts followed by debindering and sintering. Need to allow for significant shrinkage during debindering (20-50%). Produces uniform low porosity parts to high accuracy. The die for such a large part will be very costly, so not economic for one-off or low volume production runs.

(b) Rotational friction welding. One part rotated at high speed and pressed hard against the other to cause heating. Once red heat has been reached, the parts are rammed together. High accuracy, high strength. Suitable for circularly symmetric parts such as these.
(ii) Resistance Seam welding, which can be done on tinned parts. This seam needs to be flat (unlike the rolling and crimping which is used for the lids). Needs to be food-safe, so no contamination. Mass-production, so must be automated, very rapid and cheap.
(iii) Roll bonding. The soft aluminium sheet is cold-rolled to form a cold bond with the substrate. Aerospace application, so avoid stress concentrations (from rivets for example); high integrity joint needed.
(iv) Laser welding for high accuracy; resistance seam welding, TIG. All processes can be automated for mass-production. Need to avoid distortion of the thin sheet.

Examiner's comment: Descriptions of the processes in (a) (i) were generally adequate, but students often failed to explain what was happening to the material and why the processes were needed. A significant proportion did not know what ceramic powder injection moulding involved.
(b) Again, processes were generally described passably, but there was lack of discussion of why they were suitable. Quite a lot of pure guessing at processes; these were generally unsuitable, but credit was given for well-justified but incorrect answers. A particularly common error was to suggest electroplating of aluminium in (iii).

3. (a) (i) Shape classification:
Prismatic (circular, non-circular)
Sheet (flat, dished)
3D (solid, hollow)

Shape is discriminating because processes tend to be associated predominantly with one of the main 3 classes of shape, e.g. extrusion and rolling: prismatic; stamping, deep drawing: sheet; casting, forging, powder, moulding: 3D. Hence shape is effective in screening out a significant number of processes.

(ii) Main joint geometries: lap, butt, fillet. Not all are suitable for all materials. Other factors that will influence the viability of a given process-geometry combination are geometry of the components themselves (e.g. flat sheet best suited to lap joints), the material thickness (e.g. butt joints require a minimum thickness), and the mode of loading on the joint (e.g. lap joints should be loaded in shear, not bending).

Secondary design requirements for selecting joining process:

- does the joint need to conduct heat, or electricity?
- does the joint need to be easy to disassemble?
- is joining on an assembly line, or is fabrication on site? Can process be automated?
- Environment in which the joint needs to function (e.g. corrosive, high temperature)
- Cost

(c) Attributes include Technical, Quality, Economic. From attribute charts in Materials Databook, casting, forging and powder overlap to some extent on mass, section thickness, tolerance and roughness. Casting offers the greatest diversity overall, through its variant processes (sand, die, investment). Economic batch size indicates that powder processes only tend to compete at large batch sizes, while only casting variants appear well-suited to smaller batch sizes (e.g. 1-100).
(These overall trends were illustrated in lectures and examples using the more detailed attribute data in the CES software, which includes many casting variants and sub-divisions of forging and powder processes. All three classes offer viable process variants across most of the range of the four attributes listed, with economics being the most discriminating). Other considerations which relate to attributes not included in the selection charts are efficiency (e.g. material wastage) and environmental effects.

(b) Polymer-matrix composites reinforced using continuous fibres are strong in the fibre direction, but weak normal to the fibres. Strength in this direction comes only from the matrix, which is much weaker (and has a much lower elastic modulus). Out-of-plane (secondary) stresses should therefore be avoided whenever possible. Most long-fibre composites are made by lay-up of pre-preg sheets of fibres with matrix; out-of-plane stresses result in these sheets peeling apart (delamination).
Section changes always involve out-of-plane stresses. These should be minimised by tapering joints rather than having abrupt section changes. Keeping a continuous

surface 'skin' does something to protect the interior plies against delamination, and prevents ingress of liquids into the interior of the composite (wicking).
Joints are problematic. They always involve out-of-plane stresses, and composites can withstand neither tensile nor compressive stresses (fibres buckle or crush in compression). Joints need to be large and bulky to minimise stresses.
Short-fibre composites may be made by extrusion or by processes such as spray lay-up. Delamination is not generally an issue. Fibres are much more anisotropic, so secondary properties are better; joints and section changes are less likely to fail. It is also easier to design them out, since the components can more easily be made in a wider range of shapes and geometries.

Examiner's comment: Not a popular question. Part (a) was often badly answered. Many students provided brain-dumps of anything relating to the processes mentioned, rather than addressing the question, which was about classification and selection. Part (b) was straightforward, and most made reasonable attempts at it.

4. (a) Probably due to the formation of a "cold shut" during forging – at the change in section, incorrect metal flow can fold over and trap a crack-like defect. This bypasses fatigue initiation and leads to early failure. (Another contribution may be residual stress left in a hot forging that is cooled fairly rapidly, exacerbated by the stress concentration at the change in section).
Rectify by re-design of the change in section to be less severe giving more uniform deformation into the die cavity. Alternatively change deformation temperature and strain-rate to modify flow pattern. (If residual stress is involved, cool more slowly or add an annealing process afterwards to relieve the stress).
(b) Earing is due to incorrect texture in the original rolled sheet, leading to too much anisotropy in yield behaviour.
Cannot be rectified during can-making – the solution is to modify the sheet-rolling and recrystallisation processes to keep the texture to the required specification (e.g. control of rolling speed and temperature, and annealing temperature).
(Alloy chemistry also has an influence, particularly impurities such as iron and manganese - these form dispersoids that influence nucleation of recrystallisation).

(c) Surface finish can be poor if partial melting occurs at the exit from the extrusion die – the deformation heating is too great and takes the material just over the solidus temperature. Surface streaks can also be caused by damage to the tool steel die itself. Eliminate partial melting by better temperature control (e.g. reduction in extrusion speed). In some cases surface finish may be corrected subsequently by anodising. Or if die damage is the problem, repair or replace the die.

(d) A shortfall in strength after age hardening indicates a quench sensitivity problem - during cooling after extrusion coarse precipitates form, using up some of the available solute in non-hardening phases, and reducing the strength achieved after heat treatment to the peak of the ageing curve.
More severe cooling may give 100% supersaturated solid solution, provided it does not cause unacceptable distortion of the profile. Alternatively change alloy to a less quench sensitive variant (provided the resulting strength and other properties are acceptable). Quench sensitivity is also sensitive to prior processing, particularly the

homogenisation stage after initial billet casting. This generates the dispersoid particles that trigger the undesirable coarse precipitation, so a change in homogenisation practice upstream may resolve the problem.

(e) Recycled steel tends to have a higher level of impurities. Loss of ductility and grain boundary fracture in forming suggests "hot shortness" – impurities have concentrated on the grain boundaries during casting of the steel. Likely elements causing this are copper and sulphur. Copper is difficult to extract - the only solution is to check that Cu is maintained below a certain level in the recycled metal, by control of scrap mixtures used and balancing with virgin metal as necessary. Sulphur can be controlled by addition of manganese, forming ductile harmless MnS particles.

Examiner's comment: This should have been a very straightforward 'bookwork' question. Every part had been covered explicitly, and many had been asked as examples paper questions. There were good answers for every part, so there is no reason to doubt the appropriateness of the questions. However, students often failed to get the right context, and produced confident answers to a completely different question. It was difficult to find ways of awarding marks to closely-reasoned answers about completely different phenomena. There was also the usual amount of desperate flailing by the hopeful but uncertain.