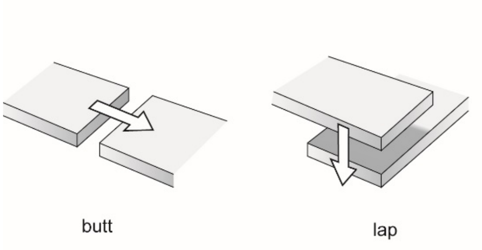
3C1/3P1 Exam

1) Welding

1) Two pieces of mild steel are butt-welded together using a standard arc welding process. The metal surfaces to be joined are shaped to create a v-shaped cavity and the joint is made using molten steel filler. The result is a full-thickness weld with a weld bead on the upper surface, as shown in Figure 1.

(a) Sketch what a *lap* weld would look like and explain why a *butt* weld configuration is preferred in this case. (10%)



Minimise the amount of filler to be used, minimises the volume of material that experiences microstructural changes due to the heat affected zone (HAZ), ensures full-thickness joint.

(b) Describe the residual elastic stress distribution around the weld, briefly explaining how it has formed. (15%)

The molten metal contracts as it solidifies and so the centre of the weld will be under tension. This elastic stress will be balanced by compressive stresses around the weld.

(c) To avoid the formation of martensite in the heat affected zone, the entire part is subject to a post-weld heat treatment to 700°C for 30 minutes, followed by quenching.

i) Explain why martensite may form and why it is a problem (10%)

Martensite may form in the HAZ as a result of re-austenitisation of the steel combined with the high cooling rates resulting from welding, which could bypass the formation of carbides. Martensite is a high strength but low toughness phase that is prone to cracking under high tensile stresses.

ii) Refer to the table and British steel CCT diagram shown in Figure 2 and 3, respectively. Would a quenching in oil from 700°C solve the problem? Consider the metal plates to be 30 mm thick and 150 mm wide (30%)

T = 30 mm, B = 150 mm, T/B = 0.2, f =1.46. De = 43.8 approx 45 mm. The quenching would not lead to any martensite in the centre of the plates. However, there could be some martensite formation at the surface, where the cooling rates are higher. SoThat could lead to crack nucleation at the surface, which may have a hard time propagating *through the entire build but would still make the part unsafe to use if toughness is a requirement.*

(d) Besides the presence of martensite discussed in part (c), what other common causes of failure could be envisioned and how could they be avoided? (15%)

Presence of defects: There may be obvious inclusions of slag, or cavities from incomplete weld metal filling. Sub-surface defects won't be visible, so for critical applications inspection techniques such as ultrasonic scanning or X-rays may be needed.

Elastic stress accumulation: Tensile stresses are frequently of the order of the fracture strength of the weld metal or the HAZ so cracking is common either within the weld bead, at the edges of the weld bead, or in the HAZ.
A post-weld heat treatment can also be used to reduce elastic stresses discussed in (b), reducing the maximum tensile stress experienced by the weld and improving fatigue lifetime.

Stress concentration: Shape weld bead to remove stress concentrations by grinding it flat, avoiding introducing additional stress concentrations from machining marks.

(e) The weld joint is dipped in molten zinc to provide a layer of zinc on the surface.

(i) What is this intended to achieve, and how does it do it? (10%)
Galvanic protection of steel by introducing a more electronegative metal which will form an anode and preferentially corrode.

(ii) The steel was found to have formed cracks close to the weld during the hot-dipping process. What is the likely cause? (10%)
Liquid metal embrittlement by zinc, which diffuses rapidly along grain boundaries in the steel. The steel fails by intergranular cracking as a result of the tensile stresses in the weld metal.

2) Casting

2) An aluminium bracket is to be produced using sand casting. The bracket is fed by a gating system consisting of a sprue, a runner, and one riser.

(a) Explain the role of the runner and riser in the sand casting process. What factors determine the size and placement of the riser in casting? (15%)

Runner:

- *Delivers molten metal from the sprue to the mold cavity uniformly.*
- *Reduces turbulence and promotes smooth flow to minimize defects like gas porosity and cold shuts.*

Riser:

- *Acts as a reservoir of molten metal to compensate for shrinkage during solidification.*
- *Prevents internal voids or shrinkage cavities in the casting.*

Size and placement factors:

- *Must solidify slower than the main casting → larger volume, smaller surface area preferred.*
- *Placed at thick sections or high-shrinkage areas.*

(b) List and briefly describe three common casting defects that could occur in casting and explain their likely causes. (15%)

Shrinkage porosity:

- *Caused by insufficient riser feed as the metal contracts on solidification.*

Cold shuts/ Misruns:

- *These are fluidity defects which occur when two molten fronts meet without proper fusion due to low temperature or poor gating, or when the liquid solidifies before filling the mould entirely.*

Sand inclusions / surface defects:

- *Caused by erosion of mold walls, poor mould compaction, or turbulence defects.*

(c) Figure 4 shows a schematic drawing of the bracket and riser assembly (all other gating elements are omitted for simplicity). The bracket is roughly rectangular, with dimensions 100 mm × 70 mm × 20 mm. The riser is a cylindrical rod of diameter 25 mm and height 50 mm. Use Chvorinov's rule to estimate the solidification time of the bracket and the riser. Assume Chvorinov's constant, B = 2 min/cm^2. Recall that Chvorinov's rule states: $t=B*(V/A)^2$ (10%)

Remember to convert convert dimensions to cm

Bracket volume:
10 × 7 × 2 cm → V = 140 cm^3
Bracket surface area: A = 2(lw + lh + wh) = 2(70 + 20 + 14) = 208 cm^2

Riser volume:
D = 2.5 cm, h = 5 cm → V = π(1.25^2*)5 ≈ 24.54 cm*^{3}
Riser surface area (top + side): A ≈ 2πr^2 *+ 2πrh ≈ 49.1 cm*^{2}

*t_Bracket: t_{bracket} = 2 * (140/208)^2 = 2 * 0.673^2 = 0.91~min*
*t_Riser: t_{riser} = 2 * (24.54/49.1)^2 = 2 * 0.5^2 = 0.5~min*

(d) From the different types of defects listed in (b), which one is likely to be found in this casting and how could it be avoided? (15%)

The riser solidifies faster than the bracket due of its high surface-to-volume ratio. As a result, we could expect to see shrinkage defects in the middle of the casting.
To avoid the problem, we should are shape the riser to have larger V/A ratio compared to the brackets so they solidify slower than the casting.

(e) Explain the physical origin of microsegregation in cast aluminium alloys and how it affects the composition and properties in different regions of the casting. (20%)

Microsegregation is the variation in solute concentration within the microstructure during solidification.

As alloys solidify, solute is rejected from the solid into the remaining liquid. The last-to-solidify region (often the center) becomes enriched in solute, leading to microsegregation.

The effects include local variations in hardness and mechanical properties. It may require homogenization heat treatment.

(f) Sketch the grain structure that you expect to see across the cross-section of the (defect-free) aluminium bracket in Figure 4. Label the different zones that you might find and explain the thermal and solidification conditions that produce them. (25%)

Near mold wall: High cooling rate → fine equiaxed grains.
Intermediate region: High level of undercooling and directional heat flow promote columnar grains growing toward the center of the casting.
Center: Cooling rate and undercooling are low, temperature gradients are small. This promotes nucleation in the liquid ahead of solidification front and coarser equiaxed grains.

3) Polymers

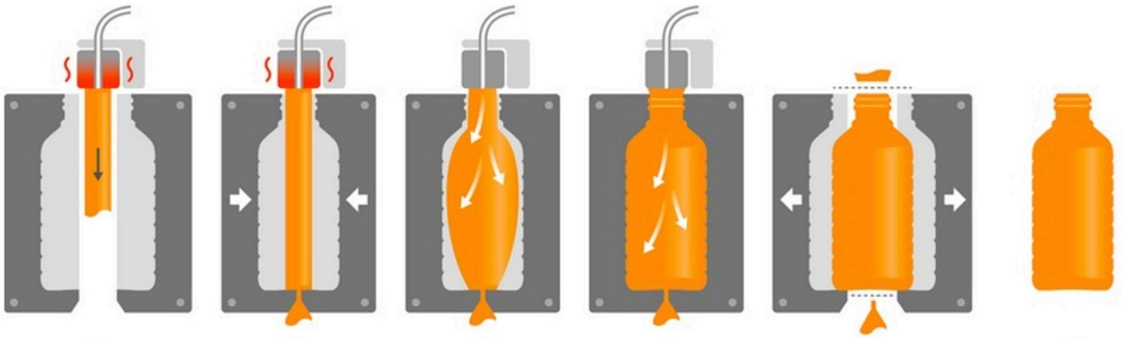
3(a) (i) Briefly describe the manufacturing processes you would choose to make a two-litre plastic bottle for carbonated drinks and a two-litre plastic bottle for milk. (10%)

Carbonated drink bottles: Stretch blow moulding. Injection moulded pre-forms are heated inside a mould, stretched longitudinally and then air pressure is used to press to the shape of the mould.

Milk bottles: Extrusion blow moulding. Hollow polymer pipe extruded into mould, air pressure used to form the bottle in a mould. Continuous process.

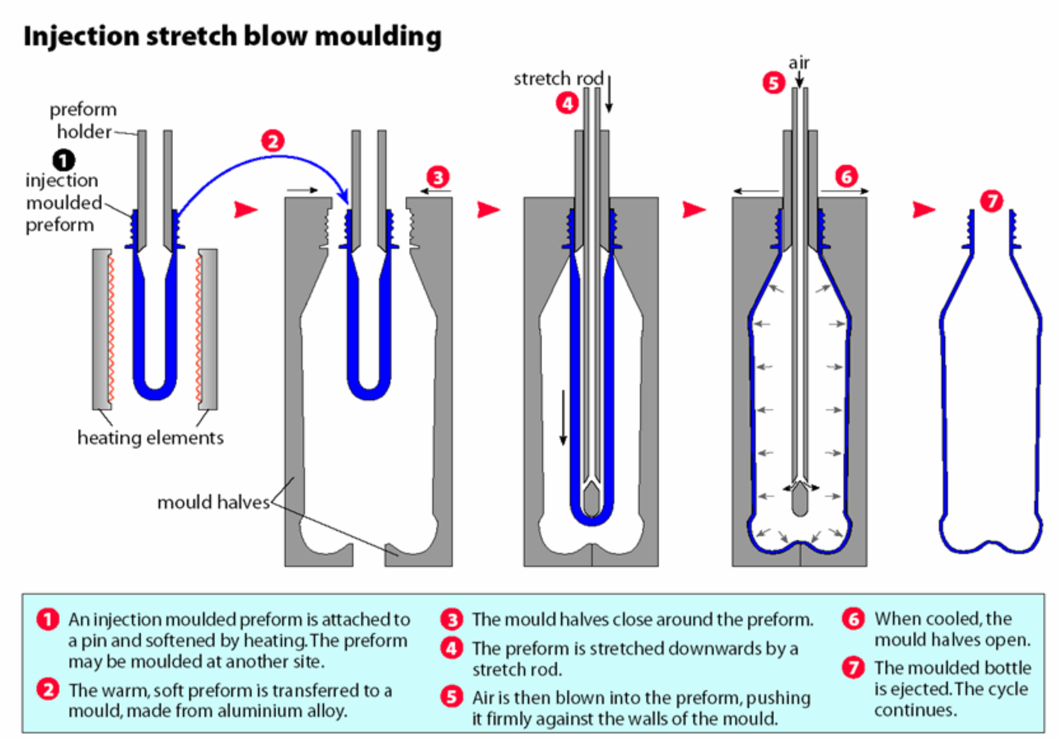
(ii) Discuss why different processes are appropriate for the two articles and what polymers you would use in both cases. (10%)

Milk bottles: Wall thicknesses are uneven, not much molecular alignment so material usage is not optimised. However, high strength is not a requirement for the application. Bottles made from HDPE: low cost material, high strength, food-safe and resistant to corrosion from milk.



Carbonated drink bottles: The stretching and blowing provide biaxial alignment in the polymer chains, increasing strength required for a pressurized bottle. Wall thicknesses are very well-controlled.

Bottles made from PET, a high-strength and relatively expensive polymer, so optimising material usage is important. PET is particularly appropriate for this application because of its low permeability to CO_2.



(ii) Discuss the extent to which these bottles can be recycled at end-of-life, and describe how this can be achieved. What are the environmental benefits of recycling these polymers in terms of carbon footprint and resource management? (15%)

Both these bottles are readily recycled, with collection and processing infrastructures in place. The bottles are collected in post-consumer domestic and commercial waste. The polymers are identified and sorting is carried out to a high confidence level. The material is shredded, cleaned and passed through a screw extruder to produce pellets that can be used for making new bottles.

If post-consumer material can be re-used to make new products of the same type, then there is saving in the amount of virgin polymer that needs to be made. Polymer is energy-intensive to make, so this is a direct reduction in carbon footprint. Polymer mainly comes from fossil resources so recycling reduces reliance on oil.
(Note: The question does not ask about management of waste plastics and plastics in the environment and natural world, so no marks are available for discussion of these aspects).

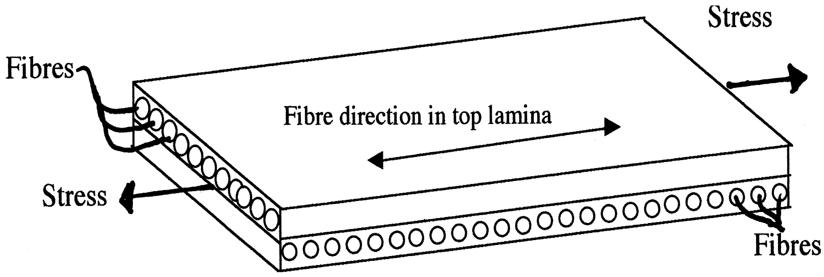
(b) Carbon fibre reinforced plastic is to be used for manufacturing a monocoque shell for a racing car. The design specifies using a high-volume fraction of uniaxially aligned carbon fibres in epoxy resin.

(i) Outline the composite manufacture and assembly process that you would recommend. Then, discuss a possible alternative manufacturing process and the corresponding drawbacks. (20%)

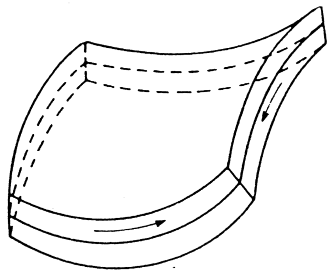
The best process will be to use pre-preg sheets comprising fibre pre-impregnated with resin which are stacked to provide the desired distribution and orientation of fibres. The stack is heated and pressed to shape, and cured (polymerization) to produce the final article. The process is largely manual and provides high-quality products.

The only realistic alternative process would be to use wet layup, whereby the fibres are laid in a mould and then impregnated with resin. This is less satisfactory because the fibre volume fraction is lower, the process requires skilled operators to achieve good quality (fibres difficult to handle; getting full penetration by resin and removing porosity difficult).

(ii) What is meant by a *balanced lay-up* and why would it be important for this application? (10%)
The mechanical properties of a uniaxially aligned lamina are highly anisotropic. The design will require stacking uniaxial sheets of fibres in different orientations, and under stress these laminae strain different amounts. Bonded multilayer panels exert high stress on each other and Poisson ratio effects mean that there is likely to be out-of-plane distortion. These can be reduced by using a symmetric lay-up (e.g. fibre orientations 0, 90, 0) so that stresses normal to the plies are balanced.



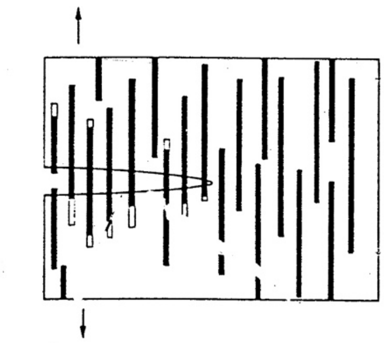
(iii)



(iii) What difficulties would you expect to encounter in joining other parts (e.g. engine, side panel) to the monocoque? (10%)
The highly anisotropic strength of the composite plies means that secondary properties (normal to the fibres and to the lamellae) are poor. Bonding anything to the monocoque (e.g. using an adhesive) would usually rely on these properties, so alternative bonding processes must be used. In addition, carbon fibre crushes very easily so fasteners such as bolts cannot be used. If holes are drilled into the monocoque the fibres are damaged, and the strength of the structure is compromised.

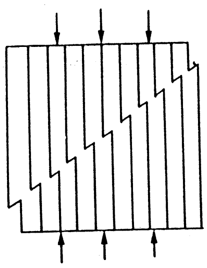
(c) Over time, the composite suffers progressive damage because of occasional impacts, cyclic loading and exposure to the environment (especially liquids and high temperatures). Discuss the type of damage that you will expect to see, making reference to how the composite has been designed to resist damage. To what extent can the damage be detected? (25%)

In service damage will build up progressively in the composite, resulting in steady reduction in elastic modulus. This can be used as a diagnostic non-destructive technique for the structure. Major delamination failures can be detected by ultrasonic or X-ray methods. Ultrasonics can be used on localised areas of complete structures, but these are more difficult to apply to large areas. The CFRP is opaque so optical methods are not helpful.



Fibres increase toughness by pulling out of the fracture surface. The work done against friction absorbs energy as the crack opens

Carbon fibres are brittle, very strong in tension but weak in compression. Structures are designed to use the longitudinal fibre strength in tension as far as possible. Toughening mechanisms need to ensure that sharp cracks can't propagate across the structure and are either blunted or diverted. The fibre-matrix interface needs to be weak enough that cracks divert to run along this path, but strong enough to transfer load to fibres so that fibres can bridge cracks and pull out, thereby increasing toughness.



Compression

In compression the fibres crush and the structure fails by buckling and shear cracking across the whole composite structure. In a complex structure such as the monocoque there may be regions of compressive stress, so the design mush ensure that the compression failure strength is not exceeded in normal service.

The integrity of the surface of the composite component is important to prevent water or other liquids from the environment penetrating into the interior. If cracks develop between laminae (where there are always high stresses, and the material strength depends only on the weaker secondary properties) then liquids can be drawn in by capillary action (wicking') and allow easy crack extension, so accelerating damage accumulation. The composite material may be sensitive to liquids: water, fuel and oils may alter the mechanical properties of the matrix (e.g. plasticising) or causing swelling. In assembling the composite, the outer layers should always be kept as continuous sheets to avoid inter-laminar cracks forming at the surface.

4) AM

(a) Define Additive Manufacturing (AM) and explain how it differs from traditional subtractive manufacturing techniques. (10%)

Additive Manufacturing (AM) refers to the process of creating objects by adding material layer by layer, often from a 3D model or CAD design. Unlike subtractive manufacturing, which involves removing material from a solid block (e.g., milling, drilling), AM builds the product up from scratch by adding material

The key difference is that AM is more material-efficient and allows for complex geometries, while subtractive processes tend to waste material and are constrained by the starting shape of the raw material.

(b) Discuss the importance of additive manufacturing in aerospace products development. (10%)

AM allows for lightweight and complex parts, such as turbine blades and airframe components, that reduce weight and improve fuel efficiency.

(c) Describe the working principle of PBF technology. (15%)

Powder Bed Fusion (PBF) is an additive manufacturing process in which a thin layer of metal powder is spread across a build platform and selectively fused using a focused energy source, typically a laser or an electron beam. The energy source scans the layer according to a digital model, melting the powder only where solid material is required. After each layer is fused, the build platform lowers, a new powder layer is applied, and the process repeats until the part is complete. Unfused powder supports the part during fabrication and is removed after the build, followed by any required post-processing such as heat treatment or machining.

(d) PBF technology includes both laser- or electron-beam processes.
(i) Explain how and why the surface quality of parts produced by these two processes differ. (10%)

Parts made by laser PBF generally have better surface quality than those made by electron beam PBF. Laser PBF uses a smaller, more precisely controlled energy spot and operates on a cooler powder bed, which limits powder sintering outside the melt track and produces finer surface features.

Electron beam PBF operates at a much higher powder-bed temperature and with a larger beam spot, causing surrounding powder to partially sinter and adhere to the surface, resulting in a rougher, more textured surface.

(ii) Explain how and why residual stresses in parts produced by these two processes differ. (10%)

Residual stresses are typically higher in laser PBF than in electron beam PBF.

Laser PBF operates on a relatively cold powder bed, which leads to steep thermal gradients and rapid cooling as each layer solidifies. These conditions generate high thermal contraction mismatches, resulting in significant residual stresses.

Electron beam PBF uses a highly preheated powder bed and builds at elevated temperature, which reduces thermal gradients and cooling rates. This allows stresses to relax during the build, producing much lower residual stresses.

(iii) Explain how and why the microstructure of a part made of high carbon steel may change when produced by laser or electron beam PBF. (20%)

The microstructure of high-carbon steel differs strongly between laser PBF and electron beam PBF because the two processes impose very different thermal histories.

In laser PBF, the powder bed is relatively cold and cooling rates are extremely high. High-carbon steel therefore tends to form hard, brittle martensite and very fine microstructures, often accompanied by high residual stresses and a strong risk of cracking.

In electron beam PBF, the powder bed is strongly preheated and the build occurs at elevated temperature. Cooling is much slower, allowing diffusional transformations to occur. As a result, the microstructure shifts toward coarser pearlite or bainite, with reduced hardness, improved ductility, and lower cracking susceptibility.

(e) (i) Discuss the pros and cons of producing copper parts using either laser or electron beam PBF processes. (15%)

Producing copper parts using laser or electron beam PBF has very different outcomes due to copper's thermal and optical properties. Laser PBF can effectively melt copper when using high power or sources with lower wavelength (e.g., green lasers) due to the low energy coupling of infrared lasers with the material. LPBF is capable of producing fine features, thin walls, and complex geometries with reasonable dimensional accuracy.

*Electron beam PBF, in contrast, provides higher energy coupling for processing copper and is thus a more efficient melting process. The vacuum environment combined with the metal's low boiling point may lead to evaporation [*note: not necessarily covered in class. This is a bonus if noted.*]*

(ii) Which process would you chose to make parts with complex internal channels and why? (10%)

For parts with complex internal channels, laser PBF is clearly the preferred choice given the challenges associated with removing partially sintered powder particles from complex internal channels when using EBM.