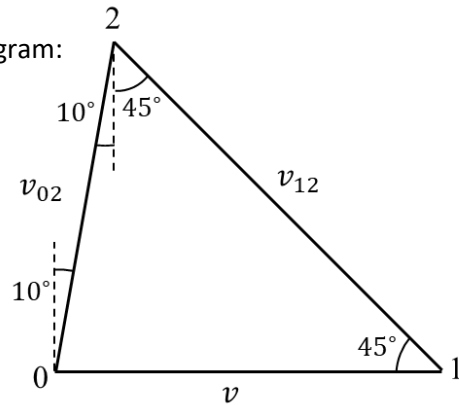
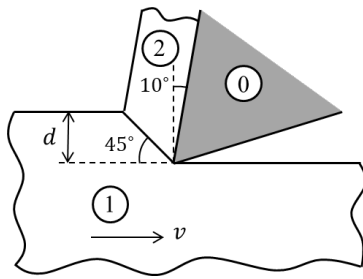


3C1 3P1 2021 Solutions

Q1. (a) (i) Machining, upper bound analysis. Velocity diagram:



Relative velocity, workpiece vs chip: $\frac{v_{12}}{\sin 80^\circ} = \frac{v}{\sin 55^\circ}$, $\therefore v_{12} = 1.202v$

Length of the primary shear zone: $L_{12} = d\sqrt{2}$

Energy balance: $Fv = kDL_{12}v_{12} = kD\sqrt{2}(1.202v) = 1.70kDdv$

(ii) Tool design:

- Sensitivity of the cutting force to the rake angle (10°).
- Cutting force gives an indication of the tool hardness required.
- Temperature rise in the chip will be related to the temperature rise of the tool, which has implications for the tool alloy choice and heat treatment.

Processing conditions:

- Predicted temperature rise can be compared with the melting temperature of the bar: melting would be detrimental to surface finish.
- The analysis gives a relationship between this temperature rise and the cutting speed (v), cut depth (d) and cut width (D).
- A refined analysis could add friction with the tool, to assess the sensitivity to lubrication.

(b) Powder processing: (i) Advantages & disadvantages vs machining.

Mechanical properties:

- Powder route gives a uniformly fine grained material, which could contribute useful grain boundary hardening.
- Uniform, fine distribution of alloy precipitates and cementite particles giving improved mechanical properties
- Powder route may however introduce some porosity, which would reduce strength and toughness.

Process economics:

- Powder route is a near net shape process, reducing material waste. Attractive for expensive alloys.
- Powder is likely to be more expensive per kg than bar stock.
- Sintering stage in a powder route carries an energy cost.
- Cost crucially dependent on batch size: minimum for powder is around 10^4 (capital-intensive equipment), but labour costs reduced since process is more automated and production rates faster.

(ii) Cold compaction followed by sintering:

Step 1 - Compaction under high pressure of metal powder plus additives to form green compact.

Significance: uniform density essential for ensuring dimensional accuracy of sintered part. Design of the mould is critical for this. Mould design must also account for significant shrinkage in sintering. Selection of appropriate particle sizes influences sintering time;

selection of appropriate particle shape influences flow properties and strength of green compact.

Step 2 - Sinter at $0.7-0.9T_m$ typically for up to one hour.

- *Significance: low porosity in final part required for good mechanical properties: tensile, fatigue and impact strength. The sintering temperature and time will influence the final porosity (and hence mechanical properties) and component shrinkage (and hence shape and dimensional accuracy). Minimum sintering time to avoid grain growth: small particle size reduces sintering time.*

Metal injection moulding:

Step 1 - Blend the metal powder with up to 50% polymer binder.

Selection of appropriate particle sizes and polymer volume fraction critical for successful injection moulding and sintering.

Step 2 - The powder-polymer blend is injection moulded to produce the green part (standard polymer injection moulding).

Binder reduces friction, reducing die wear, giving better mould filling (dimensional tolerances) and more uniform component density.

Step 3 - Binder removal, heating or use of a solvent.

Significance: must be done very carefully to ensure uniform removal without distortion of part. Limits use of process to thin sections. This is the really critical stage.

Step 4 – Sintering, as above.

Examiner's comments:

A popular question.

(a) (i) Generally well done, though some struggled with geometry (and had forgotten the sine rule).

(ii) Most discussed cutting force, and mentioned temperature rise, but did not always make reference to tool design and cutting speed.

(b) (i) Question asked about mechanical properties, but many just provided process attributes from charts in the data book.

(ii) Many did not know what MIM was, and wrote about pressure die casting instead.

Q2. (a) Thermoplastic processing:

(i) Influence of molecular structure on crystallisation:

- Molecular chain mobility required to form crystals: lower mobility results in lower crystallinity for a given temperature and time. Large side groups and branched (rather than linear) chains inhibit crystallisation. Longer chain lengths show less entanglement and so often increase ability to crystallise.
- Interactions between chains will also influence crystallisation: number and nature of Van der Waals bonds; chain entanglements. (Thermoplastics don't have cross-links between chains.)

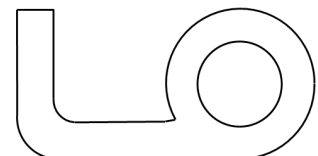
Influence of crystallinity on properties:

- Mechanical properties: High crystallinity increases the density (giving shrinkage) and increases the modulus
- Temperature sensitivity: High crystallinity reduces the softening seen at the glass transition.
- Optical properties: Large crystallites scatter light, giving an opaque appearance.

(ii) Injection moulding involves filling a closed mould (die) with liquid (but very viscous) polymer under high pressure.

Dimensional accuracy in injection moulding:

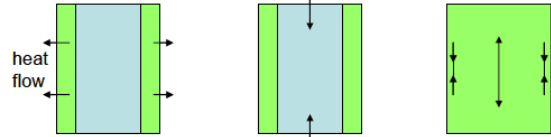
- The component has variations in section thickness that will lead to variations in cooling rate, crystallisation and therefore shrinkage.
- Redesign the part to give a more uniform section thickness.
- Increase the injection pressure and hold-on times, to compensate for the shrinkage.



- Lower mould temperatures (typically more water cooling) leads to faster cooling rates, lower crystallisation and lower shrinkage.

(iii) Residual stress:

- **Cause:** The material close to the mould wall solidifies and contracts first, forming a 'skin'. The material in the centre is still molten. This material then cools and shrinks, with the lower cooling rate enabling more crystallisation and greater shrinkage. This puts the surface region into compression and the core into tension.
- **Consequences:** Residual stresses can lead to warping and distortion of the part. They may also contribute to susceptibility to environmental stress cracking (ESC).
- **Solution:** Increase the temperature of the mould walls, to ensure more uniform cooling through the thickness (but more shrinkage). Effects are reduced with polymers that do not crystallise.



(iv) Extrusion:

- **Melt swell:** Molecular chain alignment occurs during extrusion, which can relax into a more coiled configuration on leaving the die. This causes expansion normal to the extrusion direction.
- **Solutions:** Adjust the die dimensions to allow for the expansion. Increase the length of the die 'land' (the extrusion channel) to allow relaxation of the polymer molecules within the die. Apply tension to the extruded material to maintain the aligned molecular structure until cooled. Rapidly cool the polymer at the exit of extrusion to freeze in the aligned molecular structure.

(b) CFRP fuselage panel:

(i) Balanced layup:

- In this case the plies will be arranged so that long fibres are typically oriented along the principal stress directions, enabling sufficient strength and modulus. This means that a stack of prepreg sheets in different orientations is needed, and the way in which they are arranged in the stack is the layup sequence. A balanced layup will be symmetric: e.g. for three plies the fibre orientations might be 0, 90, 0; for four layers 0, 90, 90, 0. Symmetric arrangement of ply orientations avoids double curvature and other out of plane distortions caused by an asymmetric elastic response of the layers.

(ii) Fibre matrix interface: The bond needs to be strong enough to enable load transfer from the weak, low-modulus matrix to the strong, stiff fibres, but weak enough that the fibre-matrix interface can break to enable toughness. Careful control is needed to balance these two effects.

- If the fibre matrix interface is too strong, load transfer between fibre and matrix is effective, stiffness is good, but cracks are not blunted at the interface, propagating through fibre and matrix and leading to low toughness.
- If the fibre-matrix interface strength is just right, load transfer properties from fibre to matrix are maintained, but cracks can be diverted to run along the fibre. This increases toughness.
- If the fibre-matrix interface is too weak, there is poor load transfer, and the stiffness and strength is reduced.

Examiner's comments:

(a) Most answers demonstrated some understanding of what crystallinity in polymers is and the influence of cooling rate on ability to crystallise, but the descriptions and explanations were often very unclear and incomplete. There was a lot of confusion with mould design considerations for pressure die casting (metals): injection moulding of polymers does not suffer from turbulence or air entrapment, and shrinkage commonly results in distortion rather than tearing.

(b) Many answers to (ii) didn't address the load transfer aspects but focused only on interface failure and environmental effects (wicking).

Q3. (a) Rapid corrosion of the uncoated mild steel around fastener 1:

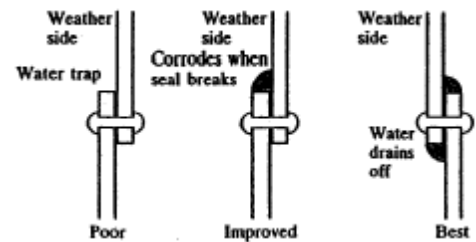
- **Problem 1:** The design of the joint makes the gap between the steel plates a water trap. This could promote wet corrosion, due to differential aeration in the crevice.

Anode equation: $Fe \rightarrow Fe^{2+} + 2e^{-}$

Cathode equation: $2H_2O + O_2 + 4e^{-} \rightarrow 4(OH)^{-}$

Rust $Fe(OH)_2$ may also form in the crevice, wedging the crack open and increasing stresses.

- **Solution:** Reverse the order of the plates at fastener 2, to remove the water trap. A sealant could also be added to prevent water entering the gap.

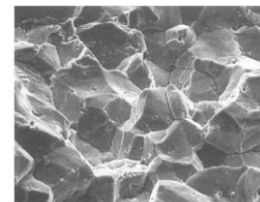


- **Problem 2:** The copper coating can encourage bimetallic corrosion. The copper coating becomes the cathode, and the uncoated mild steel becomes the anode, concentrating the oxidation reaction there.
- **Solution:** Add an insulating layer between the dissimilar materials to prevent electron flow. The mild steel could be painted to provide a protective layer.

[Tretheway & Chamberlain, Corrosion for Science and Engineering, Longman 1995]

(b) Brittle failure of fastener 2:

- **Cause:** Brittle failure indicates hydrogen embrittlement during the electroplating process. High strength materials are more susceptible. If both fasteners are embrittled, fastener 2 may fail first due to the high mechanical loads at that joint.
- **Solution:** Use a less susceptible material for the bolt, such as a lower strength steel. Reduce any residual stress arising from the manufacture of the bolts. Redesign the joint to reduce stresses and stress concentrations on the bolts. Heat after electroplating to remove any dissolved hydrogen.



Intergranular failure from hydrogen embrittlement in high-carbon steel

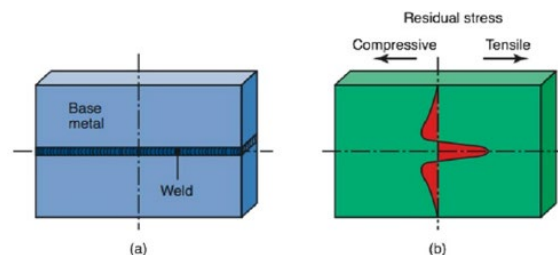
Scale: Grain diameter approx. 0.1mm

[Handbook of Case Histories in Failure Analysis, Vol 1, K.A. Esakul, Ed. ASM International, 1992]

(c) Seam welded joint (not through-thickness):

(i) Residual stress:

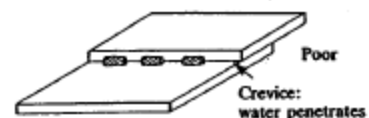
- Tensile stress in the weld, balanced by compressive stresses in the surrounding metal.
- Caused by the surrounding metal constraining shrinkage of the weld metal as it first solidifies and then cools.



[Kalpakjian and Schmid, Manufacturing processes for engineering materials, Prentice Hall, 2003]

(ii) Discontinuities in the seam:

- Stress concentrations could promote growth of pre-existing cracks in the weld bead, further promoted by residual stresses.
- The gaps could provide a route for water to enter the joint, promoting crevice corrosion.



(iii) Cracking in the HAZ, but only the electroplated side:

- Low C mild steel has a very low hardenability, so even with grain growth in the HAZ, brittle phases are unlikely to be present. In any case, if this were the cause then there would be cracking on both sides of the weld.
- Cracking is more likely to be caused by liquid metal embrittlement during welding. Melting point of copper is around 1000, while steel melts at 1500 so the copper coating in the HAZ close to the weld will melt.

Examiner's comments

(a) Answers showed weak understanding of basic electrochemical corrosion processes, although the better answers did correctly identify crevice corrosion and differential aeration as the mechanisms. Few noticed the possibility of an electrochemical couple involving the copper plating, and those that did frequently said that the copper would corrode and protect the iron.

(b) Electroplating is a room-temperature electrochemical process, in which copper is plated out on the mild steel as a cathodic process. Many answers incorrectly referred to molten metal (hot dipping is also used as a coating process) and proposed liquid metal embrittlement as the mechanism.

(c) (i) Few answers discussed the main effect here, which arises from contraction of the liquid metal in the weld pool as it solidifies.

(iii) Most answers correctly stated that mild steels have low hardenability. Explanations that did address why cracking was found only on the electroplated side proposed hydrogen cracking as the mechanism. This is not likely because mild steel is not strong enough to be susceptible.

Q4 The role of alloying additions.

(a) Si in Al casting alloy.

(i) *component size and form freedom?* yes

- positive: near eutectic, reduced freezing range, fluidity benefit

(ii) *mechanical properties?* yes

- on balance positive: second phase precipitates provide higher hardness, but toughness is reduced compared with pure Al. (Modifying the size and shape of the silicon precipitates by adding sodium as a 'poison' increases the toughness.)

(iii) *process economics?* yes

- positive: near eutectic, lower melting temp, lower energy costs

(b) S in free machining steel.

(i) *component size and form freedom?* no

- no significant influence

(ii) *mechanical properties?* yes

- negative: brittle inclusions reduce toughness

(iii) *process economics?* yes

- positive: reduced cutting forces, reduced wear on tool, faster machining

(c) W in high alloy steel.

(i) *component size and form freedom?* yes

- positive: higher hardenability, permits through hardening of larger components, less thermal distortion

(ii) *mechanical properties?* yes

- positive: higher hardness (as well as hardenability), temperature stability when tempered

(iii) *process economics?* yes

- negative: higher material cost, large alloy %

(d) Ni in austenitic stainless steel.

(i) *component size and form freedom?* no

- no significant influence

(ii) *mechanical properties?* yes

- positive: solid solution hardening, stabilisation of the austenite phase to low temperatures maintaining ductility

(iii) *process economics?* yes

- negative: adds to material cost, large alloy %

(e) Ti in microalloyed steel.

(i) *component size and form freedom?* yes

- positive: improves weldability

(ii) *mechanical properties?* yes

- positive: small alloying addition forms stable carbide particles (TiC) which prevent grain growth during welding, reducing the hardenability and so the likelihood of the formation of brittle phases (martensite).

(iii) *process economics?* yes

- positive: reduces the need for other measures to maintain weldability, such as pre-heating to reduce cooling rates.

Examiner's comments

A lot of detail was required here, and although there were some excellent answers there was also a lot of guessing. Credit was given for anything that was correct.

C Y Barlow