Part IIA module 3C1 (MET paper 3P1) 2023 solutions

Q1. (a) Attributes of the bearing race to consider when selecting a material and processing route:

- Technical: Hardness must be sufficient to resist indentation due to contact with the rolling elements. Wear resistance must be sufficient for the design life of the bearing. The material must be tough enough to resist cracking in service, or in the event of impact loads.
- Quality: Low surface roughness required, to reduce rolling resistance. Dimensional tolerances need to be high enough to accurately constrain the rolling elements.
- Economic: The target component price will influence alloy choice, heat treatment and surface hardening options. Also important are the intended product batch size and required production rate.

(b) (i) Target minimum hardness of the race is 325 HV. This occurs at the slowest cooling point on the race. This would therefore be the hardness at the centre of a circular bar with diameter D_e.

Using the CCT diagram provided for BS 503M40 (En12) steel, draw a line horizontally at 325HV. Find the intersection with the hardness curve corresponding to tempering at 550 °C for 1 hour. Draw a vertical line through this point. This represents the cooling rate giving this hardness. To find D_e , find the intersection of the cooling rate line with the 'oil' cooled scale, and interpolate.

This gives: $D_e \approx 11.5$ mm $\quad \therefore t = D_e/1.6 \approx 7.2$ mm

Incorrect combinations include:

- Correct hardness curve, but air cooled bar: $D_e \approx 0.4$ mm $t \approx 0.3$ mm
- Correct hardness curve, but water cooled bar: $D_e \approx 17.6$ mm $t \approx 11.0$ mm
- 'As cooled' hardness curve, air cooled bar: $D_e \approx 1.9$ mm $t \approx 1.2$ mm
- 'As cooled' hardness curve, oil cooled bar: $D_e \approx 28.6$ mm $t \approx 17.9$ mm
- 'As cooled' hardness curve, water cooled bar: $D_e \approx 40.2$ mm $t \approx 25.1$ mm

(ii) The minimum hardness 325 HV will occur at the slowest cooling point on the bearing race. Across the cross-section of the race, the hardness will increase as you approach the surface, where the cooling rates are higher.

To quantify this, the surface hardening can be estimated from the left hand end of the hardness curve on the CCT diagram. After tempering, this is approximately 340 HV.

There may also be variability relative to these values due to uncertainties in hardenability, hardness and microstructure predictions from the CCT diagram (the 'hardenability band'). This may be caused by variations in composition and grain size of the component relative to the reference values used to produce the CCT diagram.

(c) (i) Increase the hardenability:

- Implementation: Change in composition, increasing the alloying and / or the carbon concentration. This works by slowing down the diffusive phase transformations.
- Advantage: A higher hardenability might allow slower cooling (air cooling), which would reduce residual stresses resulting from the quench. This might help prevent crack initiation. It would also increase the hardness of the martensite, which might improve wear resistance after tempering, and help reduce crack initiation at the contact surface. However, the original alloy already met the hardness requirements, the issue being a lack of toughness.
- Disadvantage: The effect may not be significant, as BS 503M40 (En12) already has good hardenability and hardness in the quenched and tempered condition, meeting the hardness specification. It may not provide the toughness increase that is sought, as the centre and surface will only increase further in hardness with this change.

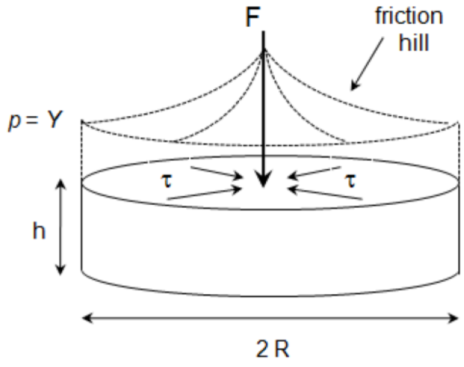
(ii) Use a surface hardening process:

- Implementation: Carburising, nitriding, laser transformation hardening would all be suitable. There is a need to maintain dimensional accuracy and smoothness of surface, so surface modification is preferable to surface coating, or processes like shot peening that would increase roughness. There is a need to treat a curved surface. The size of the contact track on the race is not be large, so area of coverage is not a critical constraint.
- Advantage: Hardening the surface would permit a lower hardness and higher toughness in the bulk of the part. This which would help reduce susceptibility to cracking, and resistance to shock loads.
- Disadvantage: It requires an additional process step vs heat treatment of the whole bearing race alone. This brings additional cost and time.

Examiner's comments: The most popular question. Most could offer correct and relevant points on the heat treatment of steel, hardenability and surface hardening. Accuracy for reading off the equivalent diameter was variable, but was marked reasonably generously. Marks were mostly lost for a lack of detail in answers, or providing generic points rather than addressing the specific questions asked. Part (c) proved most discriminating, as many described what the process modifications are, rather than specifically how (or if) they might reduce cracking, as asked

Q2. (a) Forging pressure variation across the face of the disc:

- Pressure = yield stress Y at the perimeter, where the radial stresses are zero.
- Peak pressure is in the centre of the disc.
- Pressure increases non-linearly from the perimeter to the centre due to the effect of the Coulomb friction ('friction hill').



(b) The forging load:

$$F = 2\pi Y \left(\frac{h}{2\mu}\right)^2 \left[\exp\left(\frac{2\mu R}{h}\right) - 1\right] - 2\pi Y R \left(\frac{h}{2\mu}\right)$$

To find the small μ limit, expand the term:

$$\exp\left(\frac{2\mu R}{h}\right) \approx 1 + \frac{2\mu R}{h} + \frac{1}{2}\left(\frac{2\mu R}{h}\right)^2 + \frac{1}{6}\left(\frac{2\mu R}{h}\right)^3 + \cdots$$

Neglecting terms higher than μ^3, and substituting in:

$$F = 2\pi Y \left(\frac{h}{2\mu}\right)^2 \left[1 + \frac{2\mu R}{h} + \frac{1}{2}\left(\frac{2\mu R}{h}\right)^2 + \frac{1}{6}\left(\frac{2\mu R}{h}\right)^3 - 1\right] - 2\pi Y R \left(\frac{h}{2\mu}\right)$$

$$\therefore F = \pi Y R^2 \left(1 + \mu \frac{2}{3}\frac{R}{h}\right)$$

The constant $C = \frac{2}{3}$.

To maintain equilibrium, the in-plane stress components in the disc have to balance the frictional forces on the disc surface. The in-plane stresses act over the thickness h. The frictional stresses act over the surface area of the disc, dependent on the radius R. Balancing these gives a dependence on the aspect ratio R/h. These in-plane stresses are related to the pressure acting on the disc surface via the yield criterion. The integral of the pressure over the surface area gives the forging load.

(c) Importance of controlling the temperature rise during pre-heat and forging:

- The disc must be a single phase solid solution after the pre-heat and forging steps, so that the subsequent heat treatment steps (quenching and ageing) will be effective.
- If the temperature rise during forging is too large, melting might occur, which would affect surface finish.
- If the pre-heat is too low, the material may develop coarse equilibrium precipitates, which would harm subsequent age hardening.
- The pre-heat is also important for controlling the material yield strength and forging loads.

(d) Energy balance:

$$Pt = Fh\dot{\varepsilon}t = \rho\pi R^2 h c_p \Delta T$$

$$\Delta T = \frac{Y\pi R^2\left(1+\mu\frac{2}{3}\frac{R}{h}\right)h\dot{\varepsilon}t}{\rho\pi R^2 h c_p} = \frac{Y\dot{\varepsilon}t}{\rho c_p}\left(1+\mu\frac{2}{3}\frac{R}{h}\right) = \frac{\left(50\times10^6\right)\left(10^2\right)\left(10^{-3}\right)}{2700(950)}\left(1+0.05\frac{2}{3}\frac{10}{2}\right)$$

$\therefore \Delta T = 2.3$ °C

Assumptions:

- Forging is assumed to be adiabatic, with no heat exchange with the surroundings.
- The temperature rise in the disc is assumed to be uniform.
- The force is assumed to remain constant during the 1 ms forging period. This firstly neglects the effect of the change in h and R during the period of compression. Quantifying this (not required), assuming conservation of volume to calculate the changes in h and R gives a rise in the force of about 14% during 1ms.
- The yield strength Y is assumed constant during the 1 ms forging period, i.e. we neglect any work hardening. This is reasonable if forged hot.
- Here, the low friction equation for F given in part (b) is used. Quantifying this (not required), the full equation gives a value of F around 2% higher.

Uniform temperature rise?

- Thermal diffusion times: Thermal diffusivity $a = \lambda/\rho c_p = 5.8 \times 10^{-5}$ m s^{-2} . The time for heat to diffuse the height of the disc $t = \sqrt{h/a} = 5.8$ s, which is long compared to the 1 ms forging time. So, any non-uniformity in heat generation won't even out.
- Importance of friction, as high surface friction may affect where heat is generated: $\mu\frac{2}{3}\frac{R}{h} = 0.17$ for these forging parameters, so friction is contributing 17% of the forging load, which is not insignificant.
- The temperature rise in 1ms is therefore likely to be non-uniform.

Examiner's comments: A more analytical question, and the least popular. However, the more quantitative parts, (b) and (d), were done the best. There were some lost marks due to missing terms in the energy balance in part (d). The qualitative discussions saw the largest mark variations. Marks were most frequently lost in the discussion of the temperature rise in forging, parts (c) and (d), due to lacking detail or missing key points.

Q3. (a) Cracking in the braze:

- Brazing takes place hot, so residual stresses may develop during cooling. This could initiate cracks if the braze material is incorrectly chosen, e.g. if it has inadequate toughness.
- Failure might occur at the braze-steel interface if there has been inadequate surface preparation, i.e. use of flux to remove oxide from the surface of the steel.
- Stress may develop due to thermal expansion of the pipe. This may also cause fatigue cracks in the braze if there is cyclic heating and cooling.

Corrosion of the steel:

- Cracking of the braze can mean water gets into contact with the steel under the joint. Differential aeration could accelerate corrosion within the gaps that emerge, due to relatively low oxygen concentration.
- Contact between the copper and steel will create galvanic corrosion. The steel will become the anode in the couple and the copper pipe the cathode, accelerating corrosion.

(b) (i) Thin layer of epoxy adhesive:

- Benefits:
  - The epoxy layer would isolate the copper from the steel, removing the bimetallic corrosion effect. Adhesive bonding is suitable for joining dissimilar metals.
  - An appropriately chosen epoxy (thermoset) adhesive should be able to tolerate the temperatures in the hot water pipe.
- Disadvantages:
  - Due to the curvature of the pipe, a thin layer of adhesive will only have a small contact area with the two surfaces, so the joint strength will be poor.
  - Increasing the thickness of the adhesive would increase the contact area, but thicker adhesive layers have a lower strength, so it wouldn't necessarily help.
  - A thin adhesive layer would still leave a crevice between the steel plate and the copper pipe. Water could get into the crevice, creating the opportunity for corrosion.

(ii) Galvanising the steel with zinc before brazing:

- Benefits:
  - A zinc layer would corrode in preference to the steel, protecting it.
  - The zinc would cover the whole plate, leaving no vulnerable crevices.
- Disadvantages:
  - Typical brazing temperatures exceed the melting temperature of zinc. If the zinc melts, it could lead to liquid metal embrittlement of the steel.
  - Use of a flux before brazing may also damage the zinc coating.
  - Once the zinc is consumed at the point of contact with the pipe, the steel corrosion could continue.
  - It doesn't solve the problem of braze cracks, and moisture access.

(c) (i) Polyethylene clip:

- UV exposure could lead to embrittlement of the clip, and then cracking.
- The high operating temperature could lead to increased crystallisation over time, and so a reduction in toughness. This could again lead to cracking.
- If the clip experiences elastic stresses after being clipped to the pipe, it may be susceptible to environmental stress cracking.

(ii) Thermoset clip:

- The higher modulus of the thermoset may make it less suitable for a clip that requires some elastic compliance. Compared to a thermoplastic, it would be more likely to crack or fracture when bending the clip to fit around the pipe.
- It would have more resistance to the high temperature of the pipe than a semi-crystalline thermoplastic, due to the high degree of cross-linking of the thermoset.
- It would have to be manufactured in a different way, for example moulding by placing polymer granules in a mould and heating under pressure.

Examiner's comments: A popular question, and most candidates could give some relevant points for all parts. Mark differentiation was therefore due to the level of detail and number of distinct points provided. There were few significant misunderstandings, with most marks lost due to a lack of proper explanation or providing generic details rather than addressing the specific failures described in the question.

Q4. (a) Suitability of casting routes:

(i) Pressure die casting:

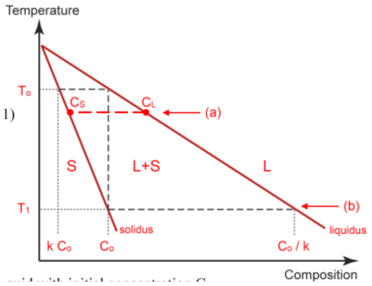
- Technical: The bead's shape would be compatible, though the process is more suitable to thinner sections. The die would have to be designed to allow ejection of the part with an internal hole, adding complexity. It's at the low end of the size and mass range for this process. The melting temperature of the alloy (not given) would need to be checked, as it would affect die design.
- Quality: This process would give a good surface finish, with low roughness. The dimensional tolerances may not be quite good enough, so the specification would have to be relaxed. It would be susceptible to turbulence during metal injection, and trapped gas bubbles, leading to porosity. The part does not experience high mechanical loads, but surface porosity would affect surface finish and lead to visible defects.
- Economic: Tooling costs would be high, making it uneconomical for a limited run of 10 items. High production rates would not be of benefit for in this application.

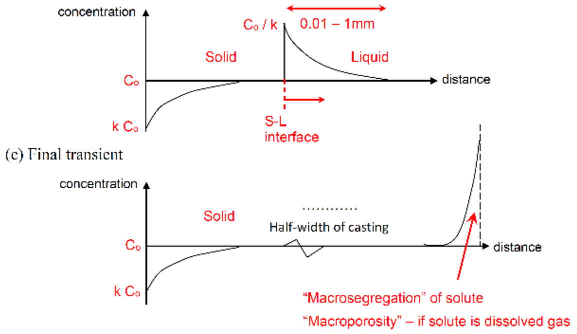
(ii) Investment casting:

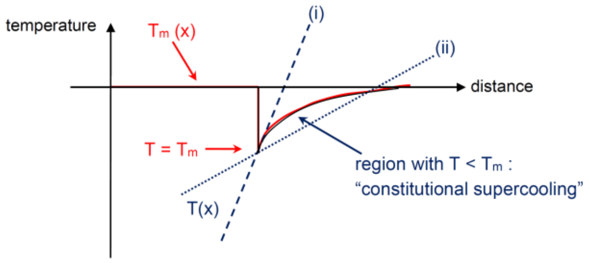
- Technical: The bead's size, mass and shape would be compatible with this process. The alloy would also be compatible, with less concern about melting temperature.
- Quality: The process would give good dimensional accuracy, and good surface finish, with low roughness. Cooling rates will be slower, which may lead to a more homogeneous microstructure, with less segregation.
- Economic: Relatively high labour costs, but acceptable for a small run of high value components. Low production rates, but acceptable for a run of 10 parts.

(b) Segregation:

- Segregation is a concentration gradient that develops during solidification. The first solid to form has a low concentration than the alloy. If following equilibrium, the concentration of the solid progressively increases, reaching the alloy concentration at the solidus line.
- However, diffusion in the solid is slow, so this redistribution of solute does not occur in practice. A concentration gradient remains trapped in the solid. Impurities also remain within the liquid, to be deposited in the final solid to form.
- This can occur at a grain level, with a gradient from the centre to the grain boundary ('microsegregation').
- It can also occur on a casting level, with a concentration gradient from the mould walls (solidifying first) to the centre of the section ('macrosegregation').
- The mould material affects cooling rates. A lower cooling rate leads to a lower temperature gradient within the liquid. This can lead to constitutional supercooling, when the temperature is below the local melting temperature, which is affected by the solute concentration ahead of the solidification front. This leads to dendritic growth. Dendritic, versus planar, growth influences the distribution of solute, and the length scales of segregation.







(c) Laser powder bed fusion (LPBF) additive manufacturing:

(i) Process suitability, and competitiveness with casting:

- Quality: Surface finish may not be as good as casting, with adhesion of powder particles giving surface roughness. Dimensional accuracy will be good enough with LPBF.
- Cost: Raw material costs will be higher for LPBF, as they will depend on the powder requirements. There may be more limited availability of suitable powders. LPBF is attractive for one-offs or limited production runs, as it lacks the high tooling costs of die casting, or the time- and labour-intensive nature of investment casting. LPBF equipment is expensive, but costs can be distributed over many builds.
- Material compatibility: Reflectivity of the material is important, as it affects laser heat input. Laser parameters will need to be adjusted to allow for this. Head input affects the solidified microstructure and defects, such as porosity, and would have to be carefully controlled. The alloy would need to be available in a suitable powder (particle size, size distribution).
- Shape: Care is needed with overhanging geometry features. It would be best oriented with the central hole perpendicular to the build plane. Support material may be needed for the angled edges of the bead, which would have to be removed in post processing.

(ii) Improving quality in LPBF:

- Post-processing: Heat treatment to improve microstructure, reduce segregation, and reduce residual stresses. Polishing to improve surface finish.
- Powder choice: Powder particle size and size distribution can affect surface finish, and defects such as porosity.
- Laser scanning strategy: The build speed, laser power, and laser scanning path can all affect the resulting geometric accuracy, surface finish, microstructure and defects.

Examiner's comments: A well answered question, with most candidates able to pick up marks on all parts. Part (b), on segregation in casting, was answered least well. Problems included a lack of clarity in the definition of segregation, or discussing grain size but not concentration variations. The different length scales were discussed well though. There were many good answers for part (c), which addresses a new part of the course on additive manufacturing. Some low scoring answers lacked any technical details of the process, or mixed up LPBF additive manufacturing with other powder-based processes.