Version YYSH/8

EGT1
ENGINEERING TRIPOS PART IB

Monday 13 June 2022 14:00 to 16:10

Paper 3

MATERIALS

*Answer not more than **four** questions, which may be taken from either section.*

Answers to questions in each section should be tied together and handed in separately.

All questions carry the same number of marks.

*The **approximate** percentage of marks allocated to each part of a question is indicated in the right margin.*

*Write your candidate number **not** your name on the cover sheet.*

STATIONERY REQUIREMENTS
Single-sided script paper

SPECIAL REQUIREMENTS TO BE SUPPLIED FOR THIS EXAM
CUED approved calculator allowed
Engineering Data Book

10 minutes reading time is allowed for this paper at the start of the exam.

You may not start to read the questions printed on the subsequent pages of this question paper until instructed to do so.

You may not remove any stationery from the Examination Room.

SECTION A

1 Reverse osmosis is a water purification process that uses a partially permeable membrane to separate unwanted molecules from drinking water. In reverse osmosis, an applied force is used to overcome osmotic forces. Figure 1 below shows a simplified scheme of a reverse osmosis cylinder, which consists of a membrane (only permeable to water), and two frictionless, water-tight pistons. Thus, in the cylinder enclosure, compartment-I contains un-purified water, and compartment-II contains purified water. The cylinder has a cross-sectional area of *A*, and the total length of the enclosure is *L*.

(a) Osmotic pressure (π) is expressed as $\pi = RTc$, where *R* is the ideal gas constant, *T* is temperature, and *c* is the solute concentration. Explain the physical origin of osmotic pressure, and the conditions under which the expression $\pi = RTc$ is valid. [5]

(b) Initially, compartment-I occupied half of the enclosure, with $F_{top} = F_1$ holding the compartment-I piston in a stationary position. Find an expression for the total number of moles of solute molecules dissolved in compartment-I. [6]

(c) Using (b) as the starting state, determine an expression for the minimum work needed to push the piston by $L/4$ for water purification. Explain why the expression deduced is the minimum work required for water purification. [9]

(d) State what factors could control the rate of water purification in a reverse osmosis process, and briefly give your reasoning. [5]

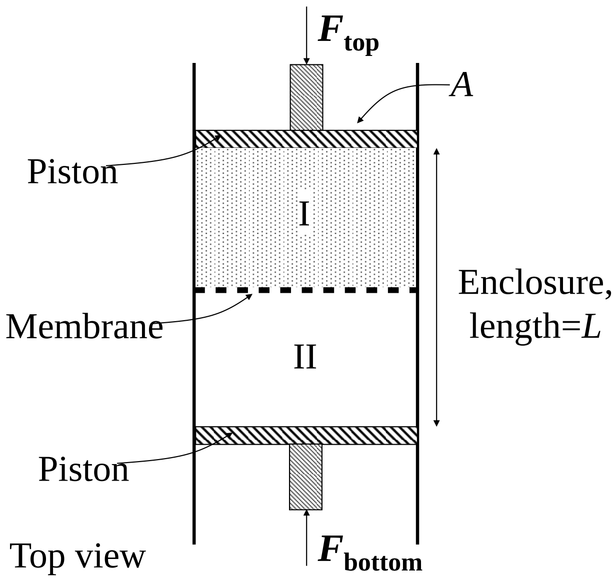

Fig. 1

2 (a) A thin patch with a finite amount of drug molecules is deposited onto the skin, where the drug molecules can gradually diffuse into the skin. The diffusion constant of the drug in skin is *D*.

(i) Sketch the evolution of the drug concentration profile in the skin depth. Your sketch should include four selected time points with relatively evenly spaced time intervals. Label key parameters on your sketch, and state your assumptions. [6]

(ii) The drug needs to be above the concentration of c_{eff}, to be effective for therapy. Plot how the therapeutic effective region in the tissue (*i.e.* tissue depth from the patch) varies over time. [3]

(iii) For the following options, which is the most appropriate form of solution to the diffusion equation describing the time-dependent drug concentration profile in skin depth, *x* (for *x* > 0):

A. $\frac{1}{\sqrt{2\pi}\sqrt{2Dt}}\left(1-\text{erf}\left(\frac{x}{2\sqrt{Dt}}\right)\right)$

B. $\frac{1}{\sqrt{Dt}}\exp\left(-\frac{x}{\sqrt{2Dt}}\right)$

C. $\frac{1}{\sqrt{2\pi}\sqrt{2Dt}}\exp\left(-\frac{x^2}{4Dt}\right)$ [3]

(iv) Based on the information from parts (a)(ii) and (a)(iii), find an expression for the time when the drug will completely lose its therapeutic effectiveness since deposition. State your assumptions. [3]

(b) Using thermodynamic reasoning, account for the following phenomena:

(i) When exposed in air, the surface of aluminium is often covered by an oxide layer, but gold is not. [3]

(ii) Graphite is commonly used as an electrode material in electrolysis and battery applications. [3]

(iii) The freezing temperature for pure water is 0 °C; however, when cooled slowly, pure water is occasionally observed to remain liquid even down to −18 °C. Upon pouring, the water freezes instantly. [4]

3 (a) (i) For a flexible polymer chain made of n monomers of length a, explain the physical origin of the mean square end-to-end distance $\langle r^2 \rangle$, and state the conditions under which the expression $\langle r^2 \rangle \propto na^2$ holds. [6]

(ii) Figure 2 shows the force f versus extension r curve of a flexible polymer of length L (where $L = na$), and that of a flexible rope of length L. Account for the key features of the two force-extension curves. What would change in the corresponding force-extension curves if the temperature increases? Use sketches to assist your answer. [7]

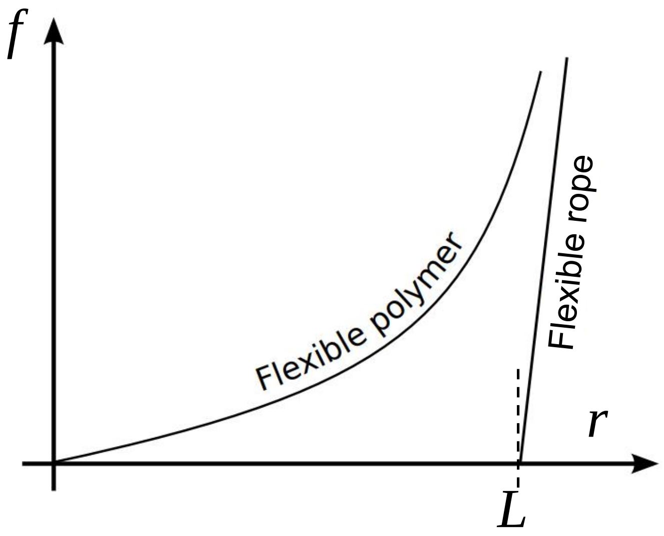

Fig. 2

(b) (i) Sketch a typical creep curve for a crystalline material, and label the key stages of creep. Describe briefly the contribution of each stage to creep life. [4]

(ii) Assuming the sketch you have drawn in part (b)(i) is obtained under temperature T_1, now sketch another creep curve which is obtained at T_2, where $T_1 < T_2$. Describe the key differences between these two curves and give your reasoning. [4]

(iii) Propose two strategies which could be used to improve the material creep life. [4]

SECTION B

4 (a) Figure 3 shows an image of a section of polished steel taken from a garden ornament.

(i) What microstructures and phases are present? Explain your reasoning. [4]

(ii) Is the steel at an equilibrium point on the phase diagram? [2]

(iii) From Fig. 3 suggest how to estimate the *wt. % C* present in the steel and provide your estimate for this value. [5]

(iv) Comment on the appropriateness of this choice of material for the application. [2]

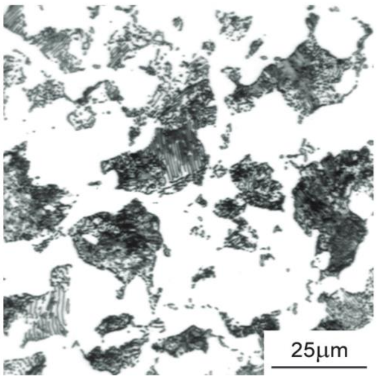

Fig. 3

(b) (i) Explain how the critical cooling rate of a steel affects our ability to thermally process it to obtain a specific hardness. [4]

(ii) Give two examples of ways of increasing the hardenability of steel. [2]

(iii) A TTT diagram for BS817M40 steel is shown in the Materials Databook (Fig. 7.3). It is subjected to a thermal process, as follows: starting at 1000 °C it is quenched to 625 °C in less than 1 second, held at that temperature for 40 minutes, and quenched to room temperature in less than 1 second. State, with reasons, which microstructures and phases are present at each of the three stages of the process. [4]

(iv) Propose, giving reasons, a thermal process that would allow BS817M40 steel to be converted into 100% bainite. [2]

5 (a) Fig. 4 shows the Bi-In phase diagram. This system is sometimes used as a low temperature solder. The molar mass of Bi is 208.98 g/mol and that of In is 114.82 g/mol.

(i) How many intermetallic compounds are shown on the diagram? Determine the chemical formulas for those you identify. [2]

(ii) Identify the peritectic, eutectic and/or eutectoid points on the phase diagram, giving the temperature and composition, in *at. % In*, at which they lie. [4]

(iii) Identify the phases present and their compositions in *at. % In* at the points A and B on the phase diagram. [4]

(iv) A 26.8 *wt. % In* alloy is provided, calculate what *at. % In* this corresponds to. That In alloy is slowly cooled from 300 °C to room temperature. Sketch how you would expect the microstructure to appear at 120 °C and at room temperature. [5]

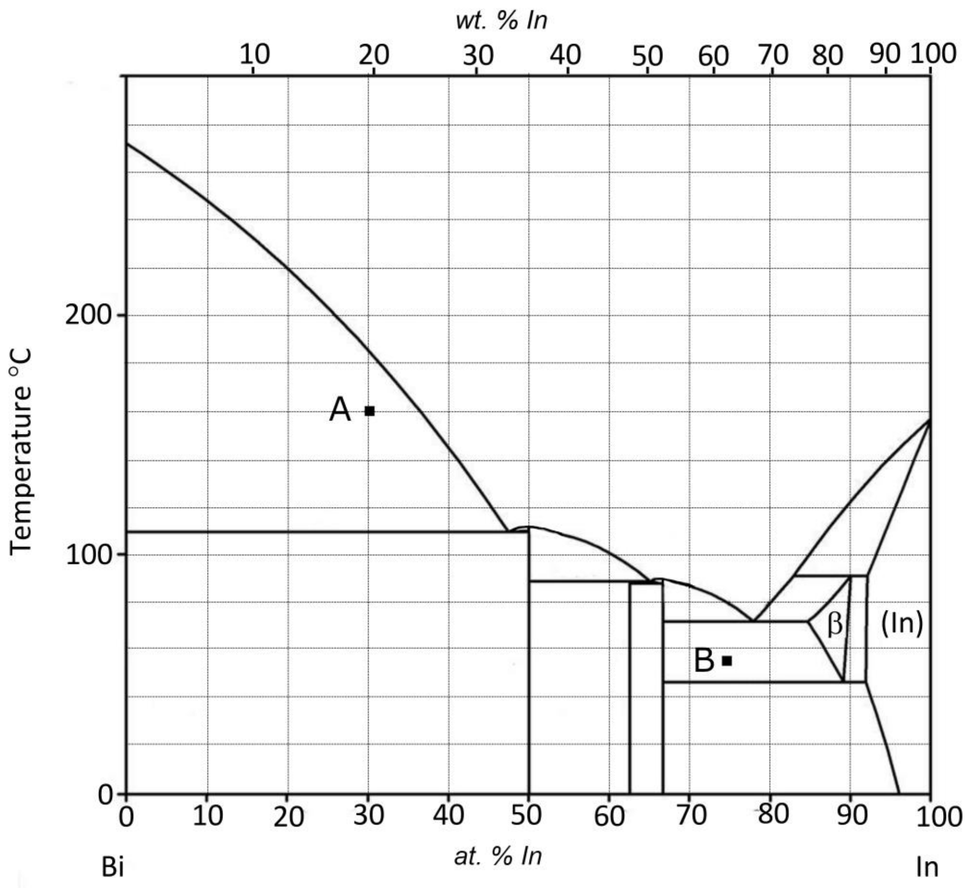

Fig. 4

(cont.

(b) The Al-Si phase diagram is provided in the data book.

(i) Explain why the concept of Gibbs free energy is useful in predicting what phases are present at equilibrium in a solid. [3]

(ii) An Al - 3 *wt. % Si* alloy is initially at equilibrium at 550 °C as a solid solution. On slow cooling to room temperature no precipitation is observed. Suggest why this may occur. [3]

(iii) Sketch, on axes of Gibbs free energy and *wt. % Si*, how you expect the Gibbs free energy of the phases present to vary at 800 °C and 600 °C. [4]

6 (a) How does the choice of either casting or deformation processing for manufacture affect the choice of metal alloy for a component? [4]

(b) A spanner, cast from Al-Si alloy, is found to exhibit a lower strength than expected. What factors, linked to the casting process, could cause a reduced strength, and how could they be addressed? [4]

(c) Explain carefully with sketches (no formal derivation required) why, in forging, a thick component will start deforming at a lower force than a thin component of the same width, given identical yield strengths? [5]

(d) A 15 mm diameter rod is used in a torsion bar suspension in a vehicle, providing the "spring" component of the suspension via twisting. The bar is required to withstand a torque of 200 Nm while retaining the ability to return to its initial position when unloaded.

[Note: The shear stress τ at radius r for an elastic bar of outer radius R under torque T is given by $\tau = Tr/J$ where $J = \pi R^4/2$]

(i) Calculate the required shear yield strength of the rod, carefully explaining your reasoning. [5]

(ii) Consequently, determine the required tensile yield strength for the material used for the rod, carefully explaining your method and any assumptions made. [3]

(iii) Which ferrous alloys in the data book would meet the strength requirement? Comment on other considerations that would need to be taken into account in selecting a suitable ferrous alloy for the rod. [4]

END OF PAPER