EGT1
ENGINEERING TRIPOS PART IB

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Monday 12 June 2023   14.00 to 16.10

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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** number 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 (a) An elastic band is made of an amorphous elastomer with a glass transition temperature of -30 °C.

(i) Sketch the relationship between modulus and temperature for the elastic band for the temperature range of -80 °C to 50 °C. Explain how this curve will be affected or unaffected by increasing the number of monomers between crosslinking points. [5]

(ii) At 20°C, the elastic band has a spring constant of $k = 10$ Nm^{-1} and a rest length of $L_0 = 15$ cm. It is clamped at one end and a mass of $m = 50$ g is hung from the other. Its temperature is increased from 20 °C to 50 °C. Estimate the direction and magnitude of the displacement of the mass. State your assumptions. [6]

(iii) Explain how decreasing the degree of crosslinking would alter the elastomer's properties and the outcome of the experiments in (a)(ii). [4]

(b) A molten thermoplastic polymer is extruded into a filament and then rapidly cooled to a solid. The cooled filament is subsequently slowly stretched to its yield point without causing filament breakage. Discuss how the following modifications to these processing conditions would change the microstructure and physical and mechanical properties of the polymer filament. You may use sketches to support your answers.

(i) Slow cooling during solidification. [5]

(ii) The cooled filament is slowly stretched beyond its yield point without causing filament breakage. [5]

2   (a)   Qualitatively explain the physical origin of the Arrhenius Law in the context of thermally activated diffusion.   [3]

(b)   Describe the following atomistic diffusion mechanisms in a solid. Use sketches to support your answers.

   (i)   Bulk interstitial diffusion.   [3]

   (ii)   Bulk vacancy diffusion.   [3]

   (iii)   Short-circuit diffusion along a grain boundary.   [3]

   (iv)   Short-circuit diffusion along dislocation cores.   [2]

(c)   A carburisation process deposits a thin layer of carbon on all faces of a large steel plate. The depth of this carbon layer is small with respect to the thickness of the plate. After carburisation, the plate is removed from the carbon rich environment. It is then heated in order to allow the carbon atoms to diffuse across the full thickness of the plate.

   (i)   Sketch the time evolution of the carbon concentration profile across the plate thickness. Your sketch should include five representative time points from time zero to infinity. Label key parameters on your sketch, and state your assumptions.   [4]

   (ii)   When the plate is heated to a temperature of T_1, the time it takes for the deposited carbon atoms to first reach the centre of the plate is t_1. What is the new expected time if the plate is heated to a temperature of T_2 instead? State your reasonings and assumptions.   [4]

   (iii)   Discuss how increasing the grain size of the steel plate will change your answer to part (c) (i).   [3]

3   (a)   (i)   Nickel can be oxidised into Ni^{2+} in both acidic and neutral aqueous environments. State the corresponding half-cell and overall reactions for both conditions.   [3]

(ii)   Explain why the rate of oxidation for nickel is likely to be lower than iron.   [3]

(iii)   Explain the role of a zinc coating when it is used for the galvanic protection of steel.   [3]

(b)   Sketch the dependence of Gibbs free energy on temperature for a pure material that undergoes phase transition from gas, to liquid, and to solid. Highlight the phase transition points, and explain the physical origin of your plot.   [4]

(c)   Figure 1 shows a typical freezing process of pure water from water to ice.

(i)   Explain why nucleation does not happen at point B, but instead at point C.   [3]

(ii)   Explain the shape of the temperature-time curve between point C and point F.   [5]

(iii)   A small amount of salt is dissolved in pure water. What are the possible changes to the positions of points B, C, D and E in Fig. 1? Explain your answer.   [4]
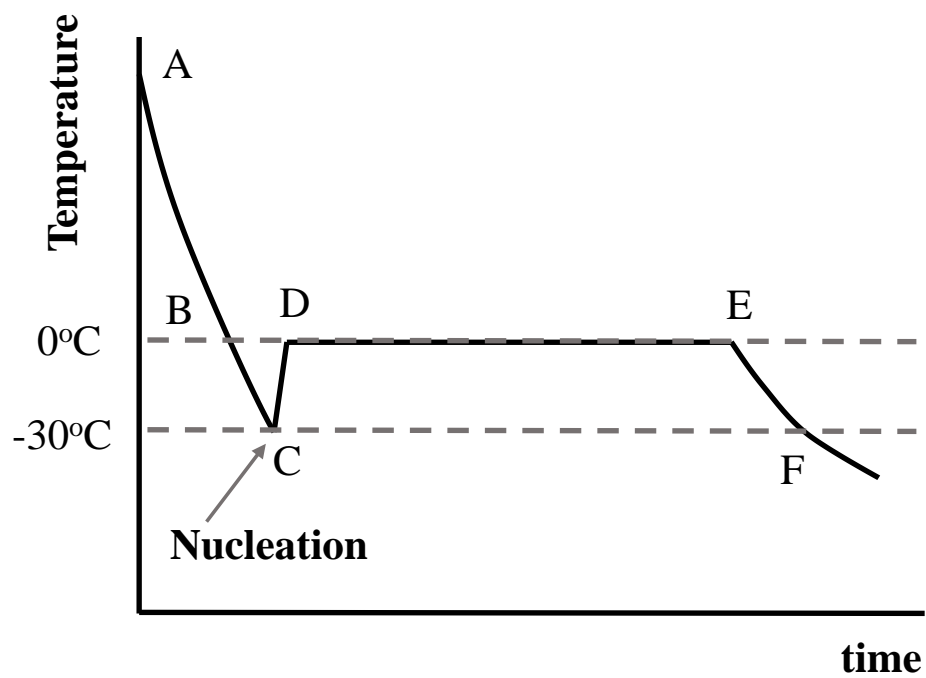
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Fig. 1

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SECTION B

4 (a) For a component undergoing creep at a constant applied stress, sketch how the strain changes over time, and label carefully the different stages of creep. Describe briefly the contribution of each stage to creep life. [4]

(b) Figure 2 shows a typical creep deformation-mechanism map for an engineering alloy. Describe briefly the mechanisms indicated in regions I to III of the map. Explain why mechanisms II and III occupy the areas indicated. [8]

(c) The blades of a gas turbine engine are to be manufactured from a nickel based superalloy with a grain size of 45 µm. The blades are initially 50 mm long. During flight, a blade experiences an axial tensile stress σ that varies linearly from 100 MPa at its root to 0 MPa at its tip, and its temperature is at a uniform value of 1000 °C. Under these conditions, it will either deform by power-law creep or by diffusion creep. In order to prevent the blade coming into contact with the outer shroud, it must not elongate by more than 1 mm over its design life of 30,000 flying hours. At 1000 °C, the creep laws for this material can be expressed as:

$$\dot{\varepsilon} = A\sigma^n \quad \text{for power-law creep}$$
$$\dot{\varepsilon} = B\sigma \quad \text{for diffusion creep}$$

where $n = 8$, $A = 5 \times 10^{-26}$ MPa^{-8} s^{-1}, and $B = 5 \times 10^{-12}$ MPa^{-1} s^{-1}, where $\dot{\varepsilon}$ is the steady-state strain rate in units of s^{-1}, and σ is in MPa.

(i) Which deformation mechanism(s) are active for this turbine blade? [4]

(ii) Determine the elongation of a blade made from this superalloy during the design life. Is this a suitable material for the blades? [5]

(iii) Describe how the microstructure could be modified to achieve increased creep resistance. Explain how these modifications could be achieved in practice. Comment on how you would expect the constants of the creep law to change. Explain your reasoning. [4]
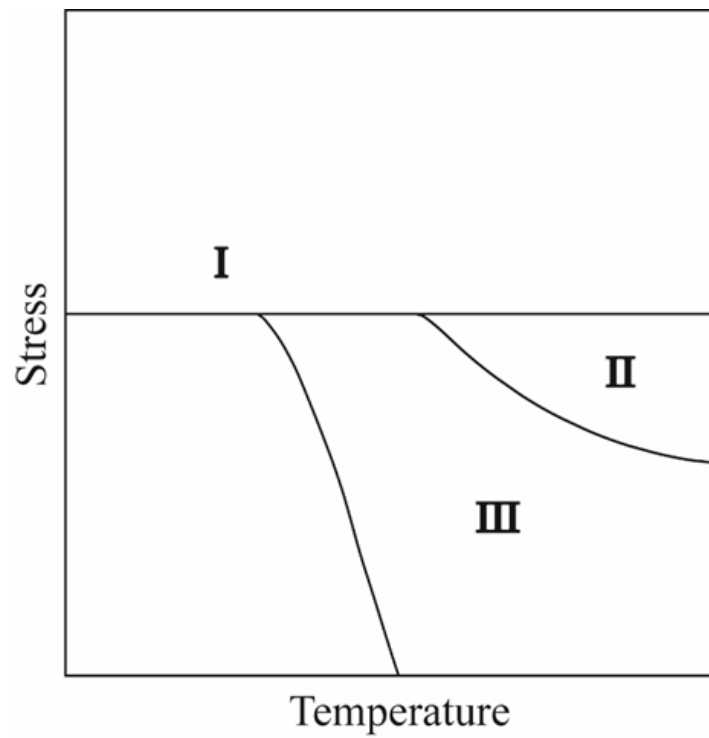
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Fig. 2

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5   (a)   Figure 3(a) shows a metal sheet being drawn through a symmetrical wedge-shaped die with faces inclined at an angle θ under plane strain conditions. The metal is a rigid-perfectly plastic material with a shear yield stress k. A force F per unit depth is required to draw the sheet against the combined resistance of a normal pressure $p(x)$ and a frictional shear stress $\tau(x) = \mu\, p(x)$, acting on the die surfaces, where x is a horizontal co-ordinate parallel to the die exit and μ is the friction coefficient.

(i)   Defining the tensile normal stress in the x direction across an elemental strip of material to be σ_x, draw a free-body diagram to show the forces acting on the strip shown in Fig. 3(b), of width dx, height $2h(x)$ and unit depth.   [5]

(ii)   By considering equilibrium of forces of the elemental strip in the x direction, show that

$$\mu p \cot\theta + p + \sigma_x + h\frac{d\sigma_x}{dh} = 0.$$

Neglect second order terms.   [5]

(iii)   Explain why the pressure p and stress σ_x can be approximately related by the equation $p + \sigma_x = 2k$. Outline any assumptions made.   [5]

(b)   A nickel alloy plate is used to manufacture a heat exchanger operating in air at 800 °C. The mass m of nickel oxide grown as a function of time t is given by $m = \sqrt{kt}$, where $k = 3 \times 10^{-5}\ \text{kg}^2\text{m}^{-4}\text{s}^{-1}$ is a parabolic rate constant. Assume that the nickel oxide forms on one side of the plate only and has the composition NiO, and that no other oxide is formed.

(i)   Calculate the time taken for 1 mm thickness of nickel to be converted into oxide.   [6]

(ii)   What is the oxide film thickness after the time calculated in part (i)?   [4]

The density of Ni is 8900 kg m^{-3} and that of NiO is 6670 kg m^{-3}. The atomic weight of O is 16 g mol^{-1} and that of Ni is 58.7 g mol^{-1}.
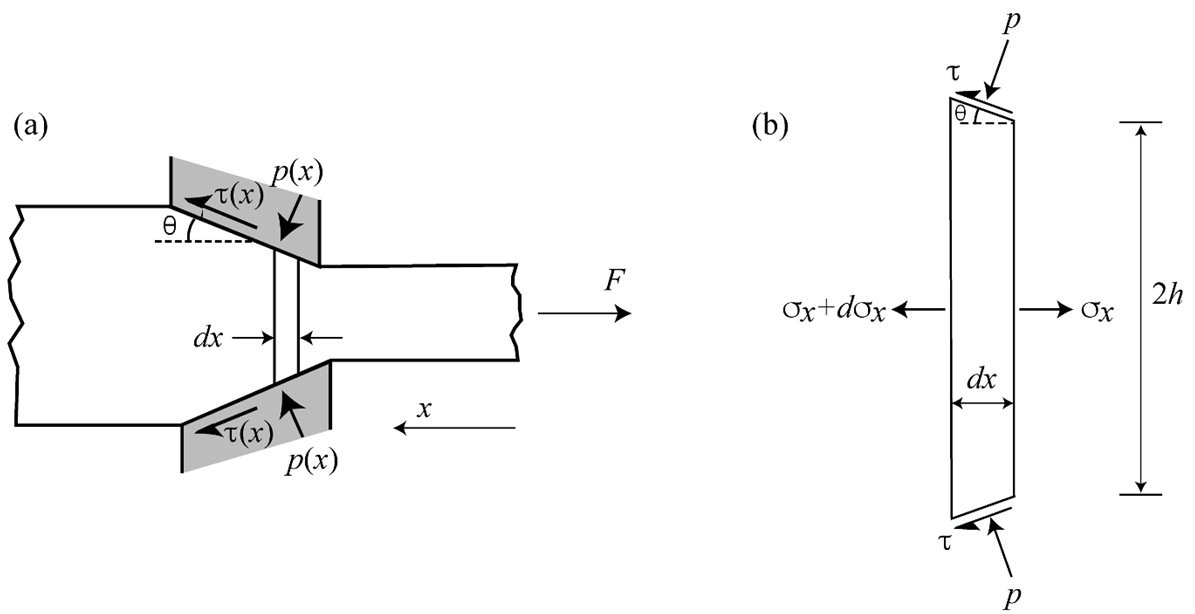
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(a)

(b)

Fig.3

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6   Figure 4 shows the equilibrium phase diagram of the system A-B. At high temperature, the system is a single-phase liquid. At room temperature, α and β are single-phase solid solutions.

(a)   Write down the phases present in *each* of the regions marked X, Y and Z in Fig.4. The phase diagram contains one three-phase reaction. State the type of reaction. For *this* reaction, write down the temperature and composition.   [3]

(b)   For an alloy containing 50 wt. % B, provide details of the microstructure, compositions, and relative proportions of the phases present;

   (i)   just above 775 °C;

   (ii)   just below 775 °C.

   Make a labelled sketch of the expected microstructure in each case.   [6]

(c)   A large volume of liquid alloy containing 50 wt.% B is slowly cooled in a large container. The system contains very few impurity particles. For solid forming far from the walls of the container, where is the first β phase likely to nucleate based on your sketch for part (b) above? Explain your answer.   [4]

(d)   A homogeneous, solid alloy containing 90 wt.% A and 10 wt.% B is cooled slowly from 775 °C to room temperature. Describe the microstructural changes that occur, noting key temperatures and phase transformations. Illustrate your answer with sketches. What is likely to be the effect on the microstructure if the alloy is cooled faster than the critical cooling rate?   [6]

(e)   Sketch schematic plots of the Gibbs free energy of the different phases as a function of composition at 1500 °C and 450 °C. On each plot, label the composition range over which the different phases are stable.   [6]
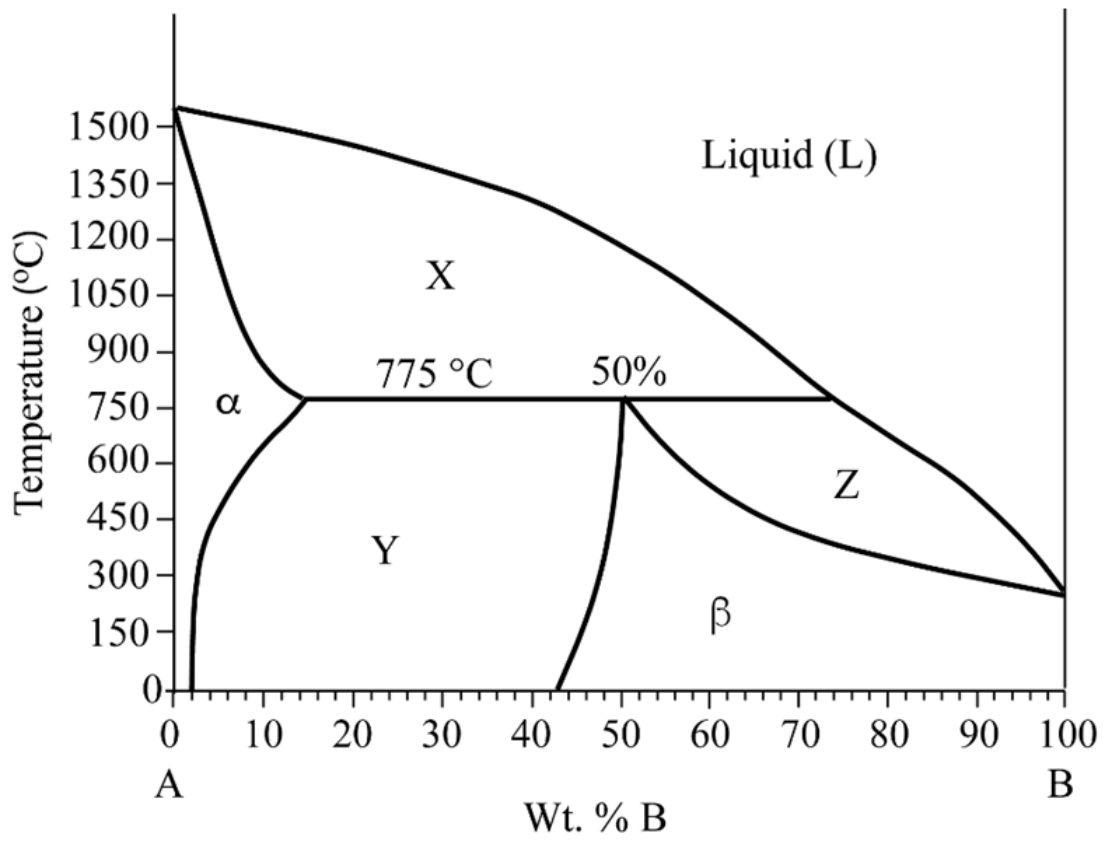
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Fig. 4

END OF PAPER

Numerical answers:

1. (a)(ii) approx. -5 mm (*i.e.* 5 mm contraction)
4. (c)(ii) 1.35 mm
5. (b)(i) $t = 4.25 \times 10^6$ s = 49.2 days
   (ii) oxide thickness = 1.69 mm

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