Version JMC/MS/3

EGT1
ENGINEERING TRIPOS PART IB

Monday 16 June 2025 14:00 to 16:10

Paper 3

MATERIALS

Answer not more than ***four*** *questions.*

Answer not more than **two** *questions from each section.*

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
Supplementary page: one extra copy of Fig. 1 (Question 2)
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 In semiconductor production, chemical ions such as boron, arsenic and phosphorous are *doped* into the silicon substrate. This requires two diffusion stages, called *pre–deposition* and *drive–in*.

The total number of dopant atoms K per unit area, deposited during pre-deposition stage is given by

$$K = \frac{2}{\sqrt{\pi}} C_o \sqrt{D_a t}$$

where C_o is the fixed surface concentration, D_a is the diffusion coefficient, and t is the duration for the pre-deposition stage.

The solution for the drive-in stage is given by

$$C(x,t) = \frac{K}{\sqrt{\pi D_b t}} \exp\left(- \frac{x^2}{4 D_b t} \right)$$

where C is the dopant concentration at distance x below the surface after time t, D_b is the diffusion coefficient and t is the duration for the drive-in stage.

(a) Explain briefly the function of the dopant ions in the semiconductor and why two doping stages are required. [3]

(b) For each of the two diffusion stages, state the boundary conditions and explain how the dopant concentration is expected to vary with time and distance, using sketches to illustrate your answer. [7]

(c) The production of a semiconductor requires boron to be pre-deposited on pure silicon at a temperature of 950°C, with a surface concentration maintained at 3.8×10^{20} atoms cm^{-3} and a diffusion constant D_a of 1.5×10^{-15} cm^2s^{-1}. Pre-deposition is followed by a drive-in stage for 1 hour at 1250°C to achieve a dopant concentration of 10^{17} atoms cm^{-3} at a depth of 2.5 μm, with a diffusion constant D_b of 1.2×10^{-12} cm^2s^{-1}.

Estimate the time required for the pre-deposition stage. State any assumptions made. [7]

(d) *Case hardening* is used to harden the surface of steel components which are subjected to high surface stresses, without compromising the strength and toughness of the underlying steel.

(i) Describe briefly how *case hardening* is achieved using the following processes: *carburising* and *transformation hardening*. Provide two examples of the use of case hardening in practice. [4]

(ii) Compare these two case hardening processes with semiconductor doping, noting any similarities and differences. [4]

2 (a) Figure 1 shows the phase diagram for the Al–Zn system.

(i) Mark all two-phase regions on the phase diagram provided and write down the phases involved in *each* of these regions. [3]

(ii) Write down the temperature and composition of the eutectic and eutectoid reactions shown on the diagram and identify the phases involved in each reaction. [3]

(b) Two Al–Zn alloys are cooled slowly to room temperature. The first alloy, an Al – 80 wt% Zn alloy, is held at 380°C before cooling. The second alloy, an Al – 90 wt% Zn alloy, is held at 480°C before cooling.

Describe the microstructural changes that occur, noting key temperatures and phase transformations, for *each* alloy. Illustrate your answer with sketches. [12]

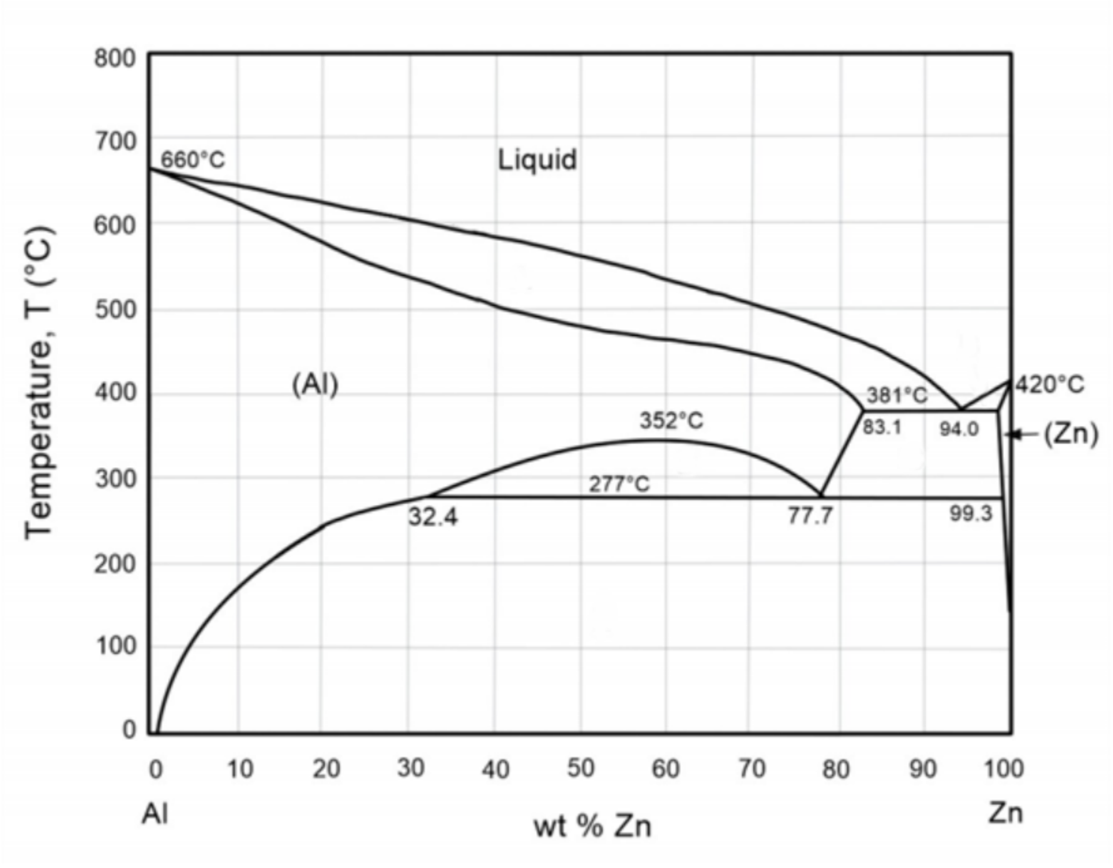

Figure 1

(c) The two alloys in Table 1 are solution heat-treated, quenched to room temperature and then reheated to 200°C and held for 5 hours. The yield strength for each alloy is given at two points: after slow cooling to room temperature, and following quenching and reheating.

(i) Using the equilibrium phase diagrams in Fig. 1 and that of Aluminium – Copper given in the Materials Data Book, suggest solution heat treatment temperatures for each alloy. [2]

(ii) Explain the differences in yield strengths between the two alloys. [5]

	Yield strength (MPa)	
	Slow cooled to room temperature	Quenched and reheated to 200°C and held for 5 hours
Al – 4 wt% Cu	100	350
Al – 60 wt% Zn	200	200

Table 1: Aluminium alloys.

3 (a) (i) Explain the reasons why (i) gold, (ii) aluminium and (iii) stainless steel, do not corrode to any significant extent under normal atmospheric conditions. [6]

(ii) Describe briefly the three common ways in which mass changes with time in corrosion. [3]

(iii) Discuss briefly the social, economic and environmental impacts of corrosion in society. [4]

(b) Describe the four conditions required for aqueous corrosion, and for each, provide an example of a method for preventing the corrosion. [8]

(c) Explain the difference between the two cathodic protection methods: passive galvanic and active galvanic (also called impressed current protection). In which situations might active galvanic protection be preferred over passive galvanic protection? [4]

SECTION B

4 (a) Consider three samples of the same elastomer at three different temperatures: $-196°$C, 30°C above the glass transition temperature (T_g), and 60°C above T_g. Rank the elastic modulus of the three samples from the lowest to the highest. [3]

(b) Briefly explain the physical mechanisms underpinning the elastic response of the elastomer in Part (a) as a function of temperature. [5]

(c) Discuss how the elastic response of amorphous thermoplastics differs from that of elastomers at temperatures $T = -196°\mathrm{C}$ and $T > T_g$. [5]

(d) Explain how varying the cooling rate during manufacturing of thermoplastics may yield different microstructure and elastic properties. [6]

(e) Discuss how applying loads to thermoplastics during manufacturing may lead to materials with improved mechanical properties (e.g., higher strength). Give one example of a processing technique that can be used for this purpose and one which does not provide this feature. [6]

5 A high-strength steel alloy to be used in nuclear power stations was subject to four different tensile test conditions to assess its steady state creep response. Two tests were performed at a fixed applied stress of $\sigma = 80$ MPa and temperatures of $T = 615°\text{C}$ and $700°\text{C}$. Two tests were performed at a fixed temperature $T = 650°\text{C}$, and applied stresses of $\sigma = 50$ MPa and 100 MPa. In each case the creep versus time was measured *only during steady state creep*. The data is shown in Fig. 2 and Fig. 3, respectively. In order to evaluate the strain rate of this material at an arbitrary temperature, T, and stress, σ, the following relationship can be used:

$$\dot{\epsilon} = A\sigma^n \exp\left(\frac{-Q}{RT}\right)$$

where A is a material constant, Q is the activation energy for creep, n is the creep exponent, and $R = 8.314$ kJ mol^{-1} K^{-1} is the universal gas constant.

(a) Use the data in Fig. 2 and Fig. 3 to calculate the steady state creep strain rate subject to each of the four test conditions. Note: time zero corresponds to the start of steady state creep. [5]

(b) Using the results from Part (a) as well as the information provided in Fig. 2 and Fig. 3, calculate the creep exponent n and the activation energy, Q. [8]

(c) Suggest which creep mechanism is at play in this steel alloy and explain the microstructural origin of it. Thus, discuss ways to improve the material creep resistance. [7]

(d) Sketch a generic plot of strain versus time during creep, indicating primary, secondary, and tertiary stages, and comment on what happens to the material during tertiary creep. [5]

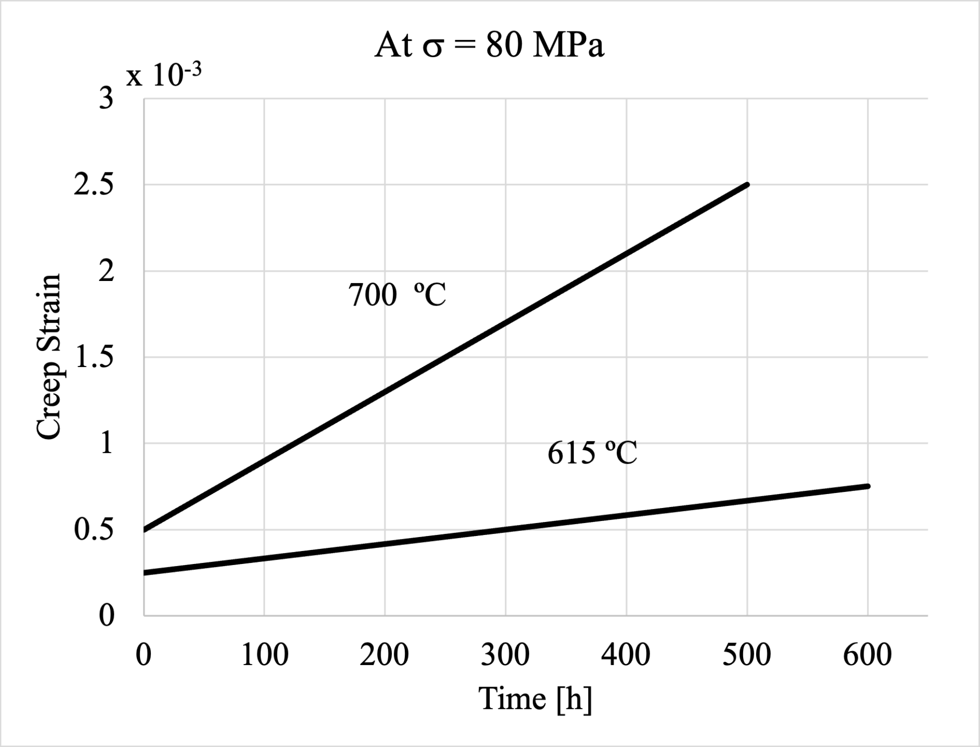

Figure 2

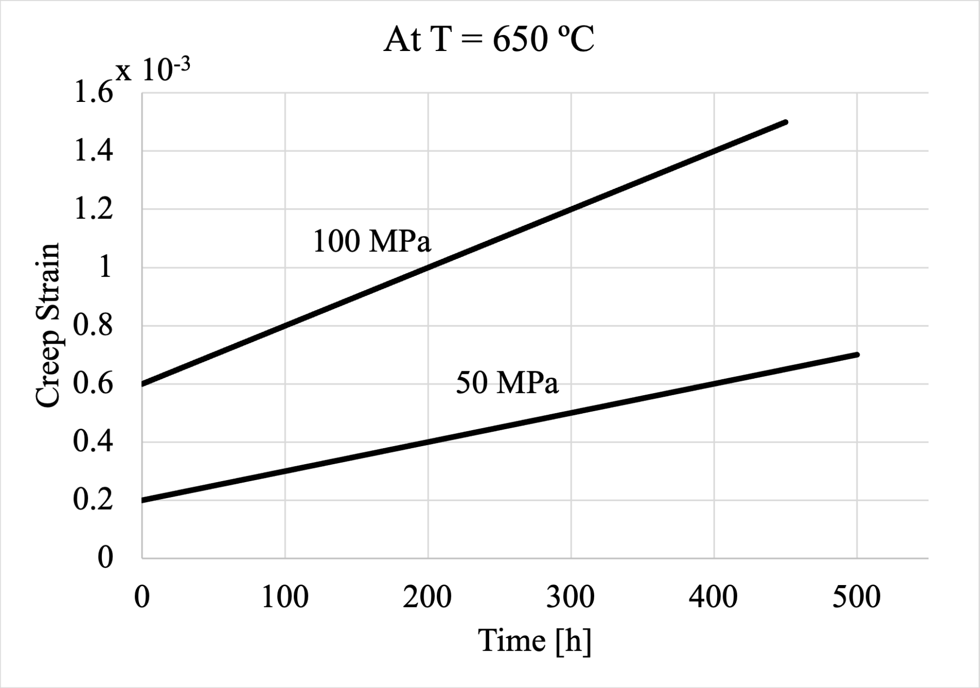

Figure 3

6 (a) With reference to the TTT diagram of the steel alloy BS503M40 given in the Materials Data Book, briefly explain the following features:

(i) The curves of fraction transformed in the 800°C – 350°C temperature range have a C-shape. [5]

(ii) In contrast to all these curves, the fraction of martensite transformed depends on temperature but not on time. [4]

(b) A sample of BS503M40 steel which was austenitised at 800°C is instantaneously quenched to 600°C, kept at this temperature for 10 minutes, and then air cooled to room temperature. A second sample of the same steel is instantaneously quenched to 400°C, kept at this temperature for 10 minutes, and then air cooled to room temperature. How do you expect the microstructure of these two samples to differ? [4]

(c) Now refer to the TTT diagram BS817M40 given in the Materials Data Book and consider a sample which was austenitised at 800°C and then cooled to 700°C in 10 seconds. As the sample is held at this constant temperature, sketch and label its microstructure after 20 minutes, 40 minutes, 3.5 hours, and 7.5 hours. [6]

(d) Explain what is meant by *hardenability* and why welding an alloy with high hardenability may raise concerns around the integrity of engineering structures. [4]

(e) By contrast, high hardenability may be an asset when designing heat treatable high strength alloys. Explain why. [2]

END OF PAPER

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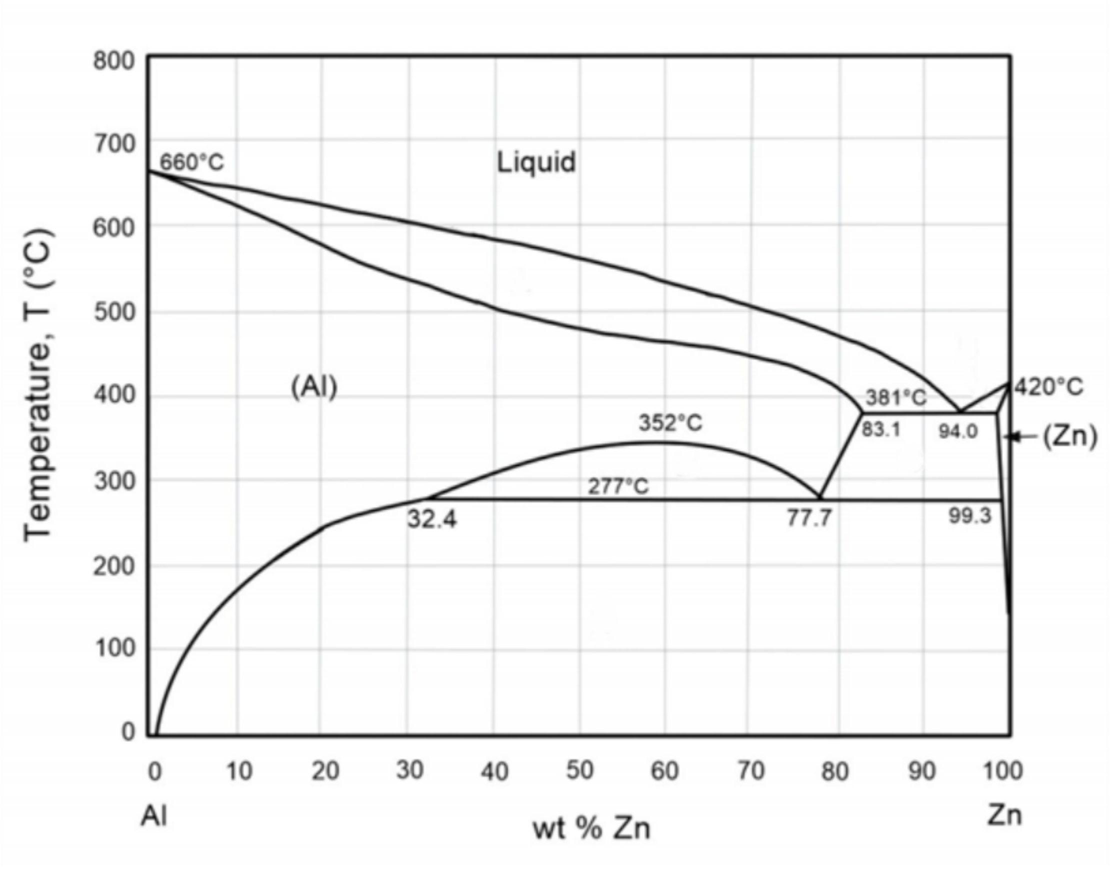

Extra copy of Fig. 1 Al-Zn phase diagram for Question 2.