

EGT1
ENGINEERING TRIPOS PART IB

Tuesday 6 June 2017 9 to 11

Paper 3

MATERIALS

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

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

*Write your candidate number **not** your name on each 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.

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

SECTION A

- 1 (a) Figure 1 shows the PbSn phase diagram.
 - (i) For an alloy with a composition of 10 wt%Sn give the phase proportions and compositions at 275 °C, 200 °C and 100 °C. [5]
 - (ii) For an alloy with a composition of 30 wt%Sn sketch the expected microstructure at 225 °C, 180 °C and 25 °C. [6]
 - (iii) For a temperature of 250 °C sketch a plot of the Gibbs free energy as a function of wt%Sn composition for the Liquid and Pb-rich solid phases. [5]

- (b) Figure 2 shows the grain structures in an aluminium casting.
 - (i) Explain how the regions of different grain morphology form during solidification. [6]
 - (ii) Describe, with reasons, how the addition of titanium oxide powder to the melt would change the grain structure. [3]

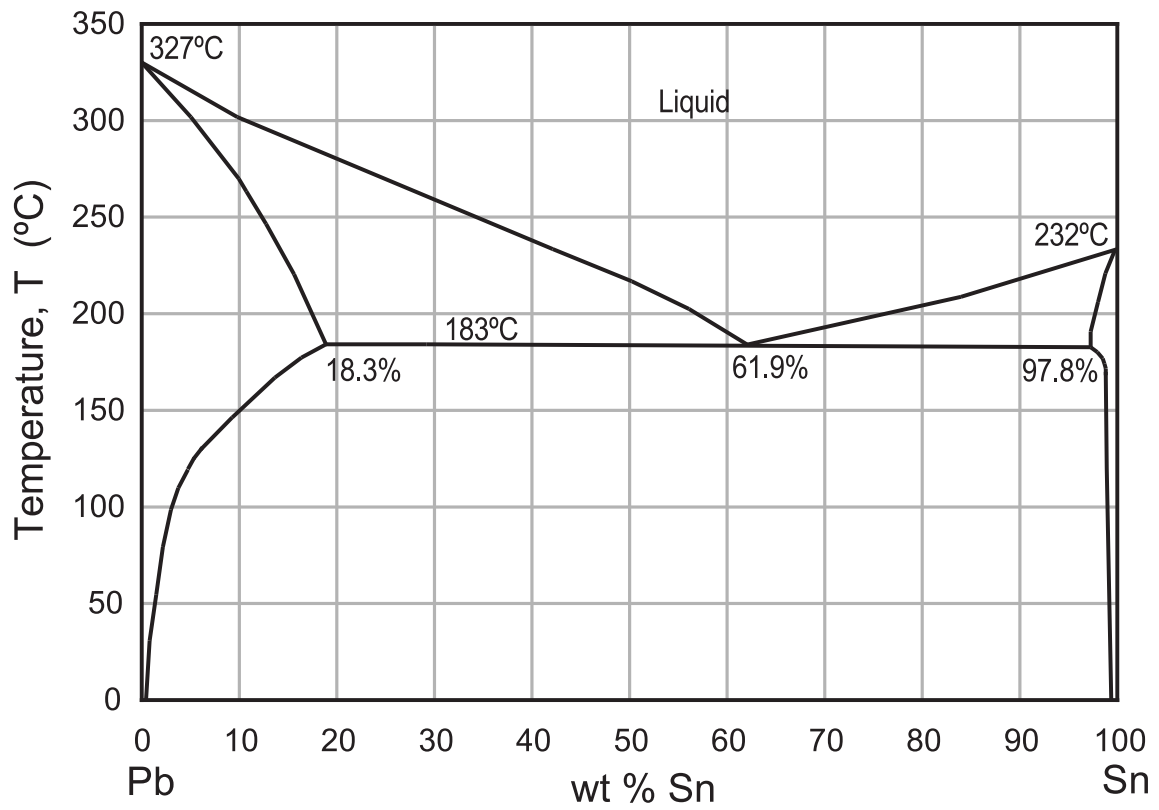


Fig. 1

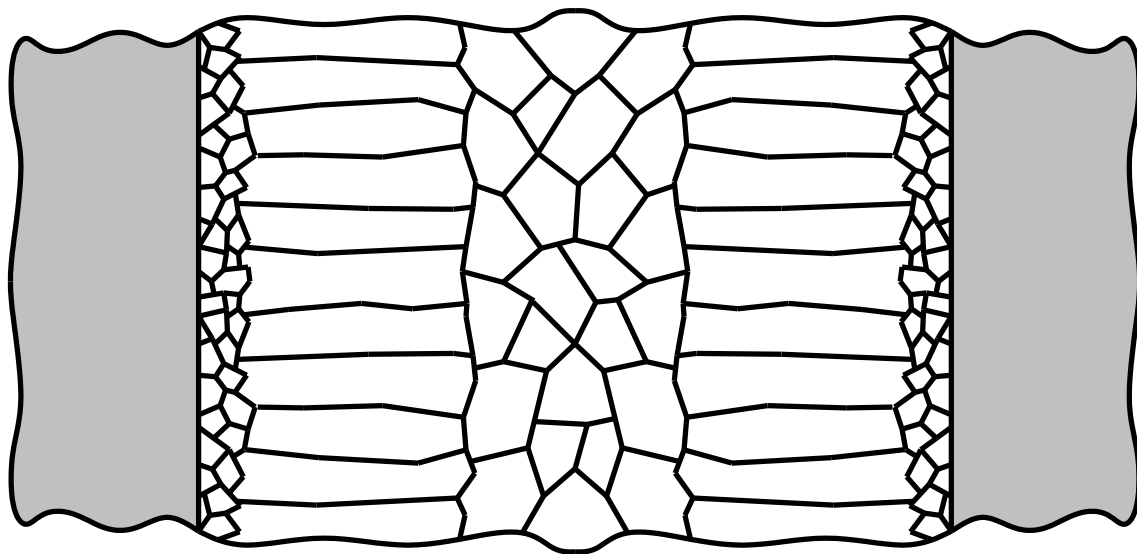


Fig. 2

2 (a) A thin sample of 0.2 wt%C steel is heated in a furnace to 1000 °C and held at that temperature for several hours. State, with reasons, what microstructure would be expected for the following subsequent thermal treatments and provide a labelled sketch:

(i) very rapid quenching to room temperature; [5]

(ii) very slow cooling to room temperature. [5]

(b) A steel cylinder of 100 mm diameter fabricated from 0.2 wt%C steel is carburised by heating in a molten bath of a cyanide salt at 1000 °C followed by quenching in water and tempering at 350 °C.

(i) Explain how the carburising treatment leads to enhanced material properties. [6]

(ii) During the carburisation the initial concentration of carbon at the surface is C_s and that inside the cylinder is C_0 . Using the fact that the variation of concentration, $C(x, t)$, with respect to depth, x , and time, t , through the cylinder is :

$$\frac{C(x, t) - C_0}{C_s - C_0} = 1 - \operatorname{erf}(x/2\sqrt{Dt})$$

calculate for how long the item must be carburised to achieve a carbon wt% of 0.6 at a depth of 0.5 mm. The diffusion constant for carbon in austenite at 1000 °C is $6.68 \times 10^{-11} \text{ m}^2 \text{ s}^{-1}$. [4]

(iii) Surface cracking is observed after the quenching step when the process above is applied to a more complex shape of a similar size to the cylinder. Explain the cause of this observation and suggest how the process could be altered to reduce the risk of cracking. [5]

3 (a) Three thermodynamic potentials (scalar quantities used to represent the thermodynamic state of a system) are:

$$\text{Internal energy (} U \text{)} \quad dU = TdS - pdV - TdS_{irrev}$$

$$\text{Enthalpy (} H \text{)} \quad H = U + pV$$

$$\text{Gibbs free energy (} G \text{)} \quad G = H - TS$$

Here, S is entropy, dS_{irrev} is the irreversible component of the change in entropy, T is temperature, V is volume and p is pressure.

(i) Derive a formula for the change in the Gibbs free energy, dG , for a system where the only work done is displacement work due to a volume change. [3]

(ii) How does the Gibbs free energy allow the most stable state of a system to be determined? [5]

(b) Water, when cooled slowly to -20°C , is occasionally observed to remain liquid. Upon pouring, the water freezes instantly.

(i) Provide a careful qualitative account for this observation. Suggest what steps can be taken to ensure that the water remains liquid reliably when cooled to -20°C . [6]

(ii) In a solidification process the difference between the free energy of the two states is ΔG_v (per unit volume of solid) and the solid-liquid interface energy is γ (per unit area). Derive an equation for the critical radius of a nucleus, r^* , in terms of γ and ΔG_v . [6]

(iii) Close to the equilibrium temperature, T_E , it is possible to deduce that $\Delta G_v = -\Delta H_v(T - T_E)/T_E$. Calculate the critical radius for ice crystals at -20°C . [Enthalpy change per unit volume of ice formed on freezing is $-3 \times 10^5 \text{ kJ m}^{-3}$, $\gamma = 0.025 \text{ J m}^{-2}$.] [5]

SECTION B

4 (a) The simplest form of polymer is that formed by polymerising ethylene to give polyethylene, as shown in Fig. 3. Give three ways in which this basic structure may be altered in order to change the properties of the resultant polymer. Give one example of how the nature of the polymer chain affects observed materials properties. [6]

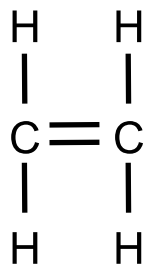
(b) It is desired to produce a transparent cover for a landing light mounted on an aircraft's nose landing gear.

(i) What properties will the material used to fabricate the cover be likely to need? Suggest a suitable polymer for the application. [4]

(ii) Considering the required properties, suggest a suitable manufacturing method for the desired part. Explain how the process chosen, and the control of that process, would lead to the required properties. [6]

(c) Sketch the stress-strain response of an amorphous thermoplastic close to its glass transition temperature, T_g . Label the key parts of the sketch and explain how they relate to the disposition of the polymer chains within the material. [9]

ethylene molecule (C_2H_4)



polyethylene chain

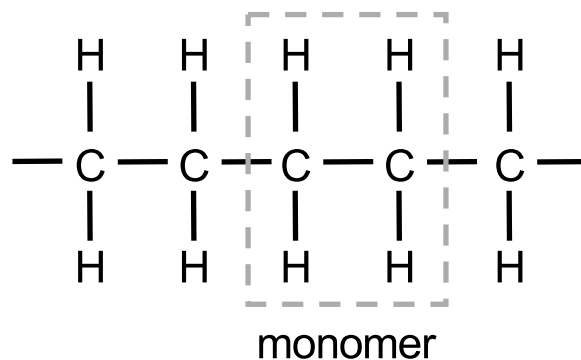


Fig. 3

5 An aluminium alloy plate of thickness d is removed from a furnace at an initially uniform high temperature, T_1 . The plate is plunged into a water bath at room temperature, T_0 , in order to quench the alloy into the super-saturated state. The bath is large and heat transfer is efficient, so it may be assumed that the surface temperature instantaneously changes to T_0 and remains constant for all times $t > 0$. The thermal diffusivity of the plate is a .

(a) (i) At the early stages of the cooling, the temperature profile at positions close to the surface of the plate can be described by the error function. By considering the boundary conditions, write down a solution for temperature, $T(x, t)$, with respect to depth, x , and time, t , for each of the two surfaces of the plate. [5]

(ii) Explain why the error function solution will only accurately describe the temperature profile through the plate in the early stages of cooling. [4]

(b) The later stages of the cooling process can be approximated by a sinusoidal function for the entire plate thickness of the form:

$$T(x, t) = T_0 + (T_1 - T_0) \frac{4}{\pi} \sin\left(\frac{\pi x}{d}\right) g(t)$$

Derive an expression for $g(t)$, assuming that $g(0) = 1$. [8]

(c) (i) Sketch how the variation of the temperature profile T with plate depth, x , for the entire plate thickness varies during the cooling process until the plate temperature drops uniformly to T_0 . Label key parameters on your sketch. [4]

(ii) Sketch the heat flux through the surface of the plate, q , versus time, for the entire cooling process. [4]

6 (a) (i) Sketch a typical creep curve for a crystalline material, and label carefully the different stages of creep. Describe briefly the contribution of each stage to creep life. [6]

(ii) Assuming the sketch drawn in part (i) is obtained at a temperature T_1 , sketch another curve for a temperature T_2 , where $T_2 < T_1$. Describe the key difference(s) between these two curves and briefly explain your reasoning. [3]

(b) The steady-state creep behaviour is described by the creep equation:

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

where $\dot{\epsilon}$ is the steady-state strain rate, A is a constant, σ is the applied stress, Q is the activation energy for creep, R is the gas constant and T is the temperature.

(i) A mass of 100 kg is suspended from a bar of a nickel alloy (density 8900 kg m^{-3}) of length 30 mm and diameter 5 mm at 1000°C . The bar is required to operate for at least 20,000 hours with a maximum creep strain of 10%. Would you expect the bar to fulfil this requirement? For this alloy and working regime; $Q = 135 \text{ kJ mol}^{-1}$, $A = 4 \times 10^{-11} \text{ N}^{-1} \text{ m}^2 \text{ s}^{-1}$, and $n = 1$. [8]

(ii) Figure 4 shows a deformation-mechanism map for a different nickel alloy. The contours are lines of equal strain-rate for steady-state creep in units of s^{-1} . For a constant temperature of 800°C and a constant stress of 10 MPa estimate the creep activation energy, Q , and the stress exponent, n , for the power-law creep regime. [8]

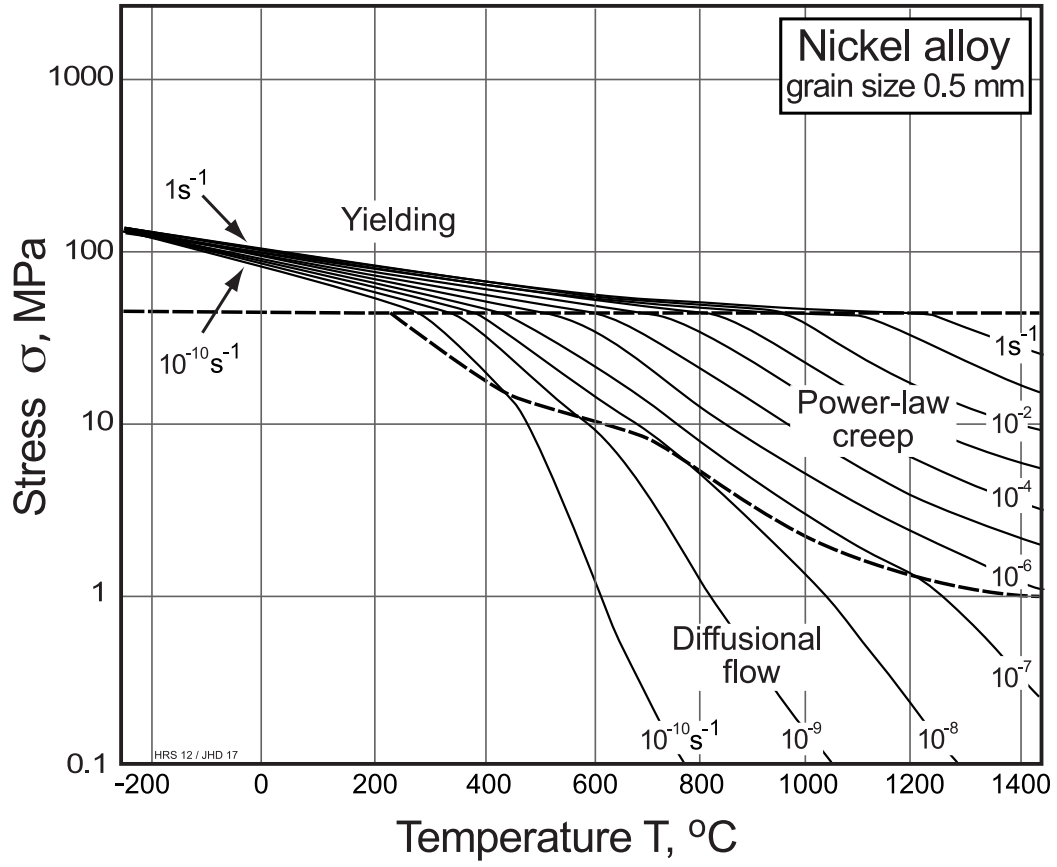


Fig. 4

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Numerical Solutions

1) i) At 275 C and 10% phases are L [23wt%Sn] and (Pb) [8wt%Sn] 2:13

At 200C just (Pb) 10wt%Sn

At 100C phases are (Pb) and (Sn). (Pb) is 3wt%Sn and (Sn) is 99%wtSn.

2)ii) 30 minutes

3)b)iii) 2.275 nm

6) b) i) 41%