ENGINEERING TRIPOS   PART IB

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Tuesday 7 June 2011   9 to 11

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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.

There are no attachments.

STATIONERY REQUIREMENTS   SPECIAL REQUIREMENTS
Single-sided script paper   Engineering Data Book
Graph paper   CUED approved calculator allowed

**You may not start to read the questions
printed on the subsequent pages of this
question paper until instructed that you
may do so by the Invigilator**

AEM_Version3

SECTION A

1   (a)   Explain briefly the mechanism by which *diffusion creep* occurs, using diagrams to illustrate your answer.   How would you choose a material to suppress diffusional creep deformation?   Explain your reasoning.   Give an example of an engineering application in which this type of creep is suppressed.   [6]

(b)   Depending on the diffusion path, diffusion creep is divided in two types; Coble creep and Herring-Nabarro creep. The steady-state strain rate $\dot{\varepsilon}$ is given by the following equations

$$\dot{\varepsilon} = \frac{D_{gb}\sigma b^4}{kTd^3} \quad \text{(Coble creep)}$$

where D_{gb} is the grain boundary diffusion coefficient, σ is the applied stress, b is the Burger's vector, k is Boltzmann's constant, T is the temperature and d is the grain size and

$$\dot{\varepsilon} = \frac{D\sigma b^3}{kTd^2} \quad \text{(Herring-Nabarro creep)}$$

where D is the bulk diffusion coefficient.

Estimate the temperature at which Herring-Nabarro creep produces the same creep rate as Coble creep for nickel with a grain size of 100 μm.

The bulk diffusion for nickel has an activation energy Q of 280 kJ mol^{-1} and a pre-exponential factor D_o of 2×10^{-6} m^2 s^{-1}.   For grain boundary diffusion, the corresponding values are $Q_{gb} = 140$ kJ mol^{-1} and $D_{ogb} = 5.7 \times 10^{-6}$ m^2 s^{-1}. The Burger's vector b for nickel is 2.5×10^{-10} m .   [7]

(c)   The steady-state creep behaviour of a nickel-based alloy of density $\rho = 8900$ kg m^{-3} can be described by the diffusional creep equation

$$\dot{\varepsilon} = B\sigma \exp\left(-\frac{Q}{RT}\right)$$

where $\dot{\varepsilon}$ is the steady-state strain rate, B 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.

A mass of 50 kg is suspended from a bar of the alloy of length 40 mm and diameter 5 mm in a creep test at 900 °C. The bar is required to operate for at least 20,000 hours with a maximum total creep strain of 5%. Would you expect the bar to fulfill this creep limitation?

For this alloy, $Q = 135 \text{ kJ mol}^{-1}$ and $B = 4 \times 10^{-11} \text{ N}^{-1} \text{ m}^2 \text{ s}^{-1}$. [7]

2   (a)   Figure 1 shows the phase diagram of the Au-Ni binary system. This system shows complete solubility above 810 °C and immiscibility at lower temperatures. The phase diagram contains regions labelled A, B and C. Write down the phase(s) present in *each* of these regions. For an Au - Ni alloy with composition 70 wt% Au, write down the phase(s) present, their composition and proportions of each phase at 1200, 900 and 600 °C.   [6]

    (b)   An Au – 10 wt% Ni alloy is cooled from the liquid state.

       (i)   Describe the microstructural changes that occur during cooling if equilibrium is maintained, noting key temperatures and phase transformations. Provide details of the microstructure, compositions and relative proportions of the phases present at 300 °C. Illustrate your answer with sketches.   [9]

       (ii)   Describe the possible non-equilibrium effects if the cooling rate was faster. Suggest how these effects can be reduced.   [5]
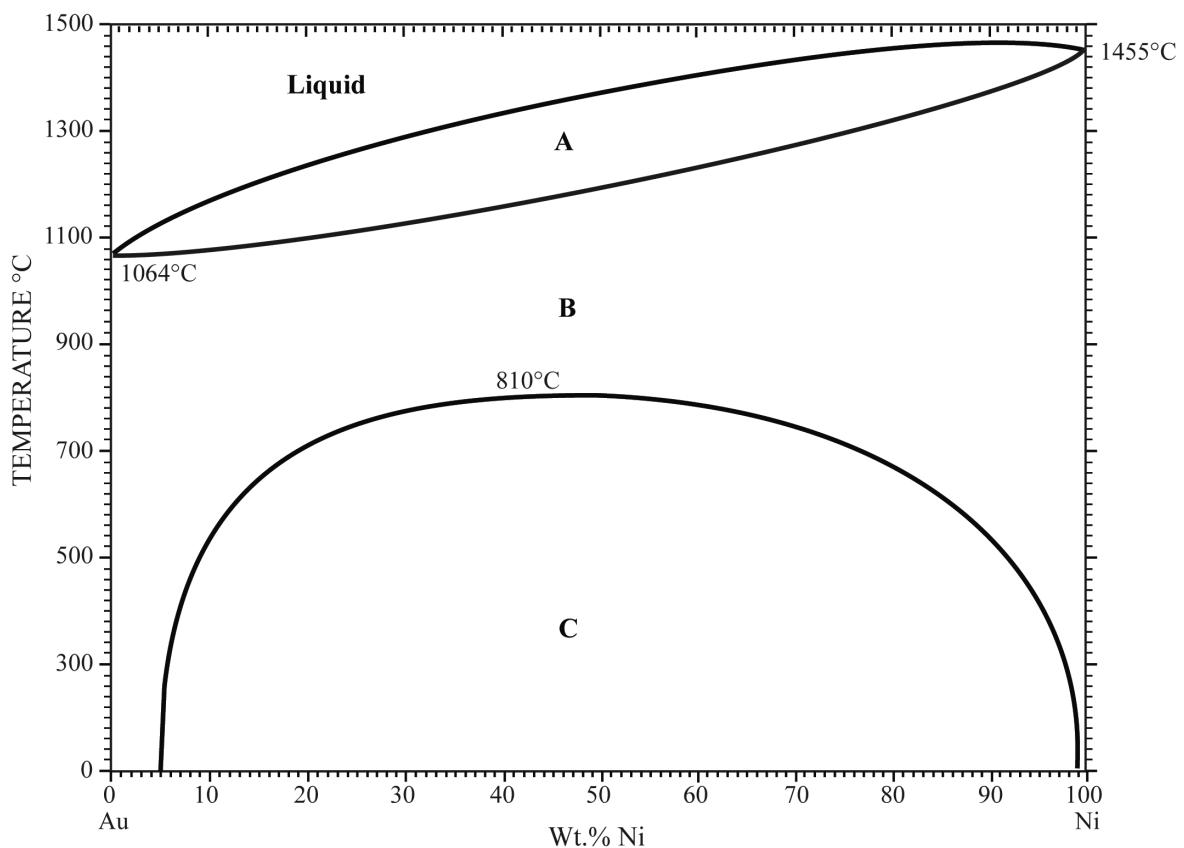

Fig.1

3   (a)   Describe the manufacturing process for producing high strength polymer fibres. Indicate the conditions necessary for this process to take place. Sketch a typical stress – strain response of the polymer during this process, explaining what happens during different stages of the deformation.   [7]

(b)   A polypropylene sheet of thickness $2h = 3$ mm is cooled from a melt at $T_m = 160$ °C to a temperature $T_0 = 40$ °C in a metal mould. The data in the table below show the temperature T at mid-thickness measured as a function of time t after the onset of cooling. Assuming that heat transfer away from the sheet surface is very fast compared to that at the centre, the data are described by the following Fourier equation

$$\frac{T(t) - T_0}{T_m - T_0} = \frac{8}{\pi^2} \exp\left(-\frac{\pi^2 a t}{4h^2}\right)$$

where a is the thermal diffusivity of the polymer.

t (s)	T (°C)
10	115
40	82
60	62
90	51
130	43

(i)   Derive an expression for the cooling rate dT/dt at the sheet mid-thickness in terms of $T - T_0$, a and h.   How would you expect the polypropylene microstructure to vary across the thickness of the sheet in the limits of high or low cooling rate dT/dt.   [5]

(ii)   Plot an appropriate cooling curve to estimate the thermal diffusivity a of the polymer.   [6]

(iii) If   the   specific   heat   capacity   of   the   polypropylene   is $c = 1100$ J kg^{-1}K^{-1} and the density is $\rho = 900$ kg m^{-3}, estimate the thermal conductivity of the polymer.   [2]

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SECTION B

4 (a) Define the term *hardenability* in the context of the heat treatment of steels. [3]

(b) Figure 2 shows a Time-Temperature-Transformation (TTT) diagram for a 0.4 C - 0.2 Mo steel.

(i) Explain briefly the general shape of the contours of constant fraction transformed. Define the terms A_3 and A_1 and identify the microstructures labelled A, B, C and D in Fig. 2. [5]

(ii) A small sample of this steel is heated initially to 840 °C and held at this temperature for 1 hour prior to heat treatment. Determine the subsequent time-temperature heat treatments required to produce 100% bainite, and 75% martensite – 25% bainite. Estimate the cooling rate that would be required to form 100% martensite. [4]

(c) A eutectoid plain carbon steel is to be transformed from austenite to pearlite at 650 °C.

(i) Estimate the maximum time for a carbon atom to reach a cementite plate in the pearlite if the process is limited by the diffusion of carbon in the austenite just ahead of the transformation interface. Assume that the plates are 3 μm apart. [3]

(ii) If a similar steel containing a small amount of chromium transforms in the same way, determine the time required for a chromium atom to reach the cementite plate in the pearlite. Explain why this differs from the values calculated for carbon. [5]

For the diffusion of carbon in austenite, the activation energy Q is 110 kJ mol^{-1} and the corresponding pre-exponential factor D_o is $2 \times 10^{-6} \text{ m}^2\text{s}^{-1}$. For the diffusion of chromium in austenite, $Q = 260 \text{ kJ mol}^{-1}$ and $D_o = 1 \times 10^{-4} \text{ m}^2\text{s}^{-1}$.
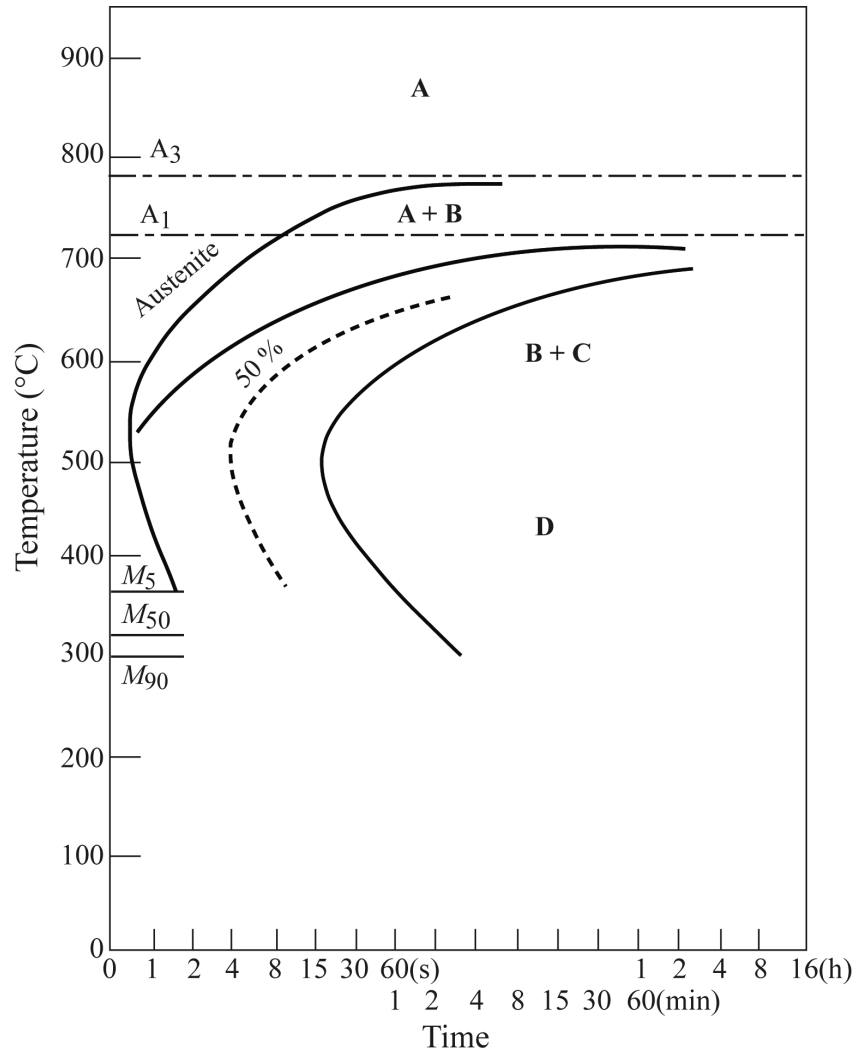
Fig. 2

5   A slab of height h and width b is forged between two parallel dies under plane strain conditions (i.e. the depth of the slab into the page is very much greater than b), as illustrated in Fig. 3. Friction exists between the slab and each face of the die.

(a)   Derive a differential equation of equilibrium for the variation of the transverse compressive stress component in the x-direction $\sigma(x)$ across an elemental strip of material of width dx, in terms of the frictional shear stress $\tau(x)$ between the slab and each die. Consider positive values of x only.   [5]

(b)   The frictional shear stress $\tau(x)$ is described by Coulomb friction, such that $\tau(x) = \mu\, p(x)$, where μ is the coefficient of friction and $p(x)$ is the pressure distribution between the slab and the die. If the slab material obeys the von Mises yield criterion $p(x) - \sigma(x) = 2k = 2Y/\sqrt{3}$, where k and Y are respectively the shear and uniaxial yield stress, show that, for $0 < x \leq b/2$, the pressure distribution is given by

$$p(x) = 2k \exp\left(\frac{2\mu}{h}\left(\frac{b}{2} - x \right) \right)$$

State clearly any assumptions you make. Sketch the pressure distribution across the entire width of the slab $(-b/2 \leq x \leq b/2)$.   [8]

(c)   Calculate the average die pressure needed to forge (under plane strain conditions) a low carbon steel slab with a uniaxial yield stress of 300 MPa, width $b = 150$ mm and height $h = 20$ mm. Assume that the friction coefficient μ is 0.1.   [7]
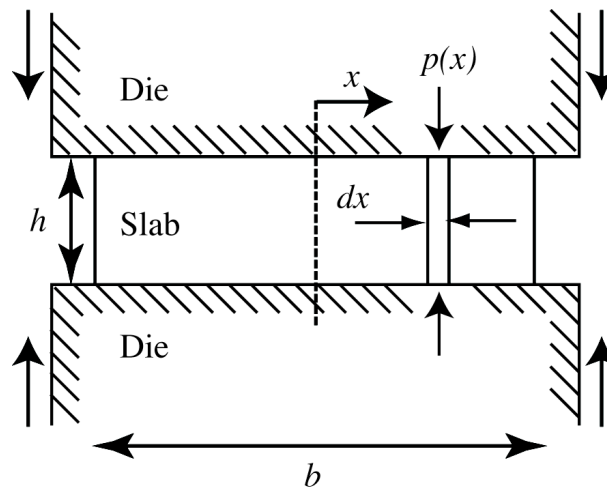

Fig. 3

6   (a)   Describe briefly the process of *transformation hardening* of a steel surface. What factors control the depth to which hardening is achieved? Compare this process with carburising. What is common between the two processes, and what are the essential differences between them?   [6]

(b)   (i) Briefly describe the two stages, *pre–deposition* and *drive–in*, involved in the doping of semiconductors. For each of these stages, state the boundary conditions for Fick's second law and explain how the dopant concentration is expected to vary with distance and time. Use sketches to illustrate your answers.   [7]

(ii)   Boron is pre-deposited on silicon at 1000 °C for 15 minutes. The surface concentration of boron is maintained at 1.1×10^{21} atom cm^{-3}. Pre-deposition is followed by a drive-in stage at 1100 °C for 1 hour.

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

$$K = \frac{2}{\sqrt{\pi}} C_o \sqrt{D\, t_{PD}}$$

where C_o is the fixed surface concentration during pre-deposition, D is the diffusion coefficient, and t_{PD} is the duration of the pre-deposition stage. The solution for the drive-in stage is given by

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

where C is the dopant concentration at distance x below the surface after time t.

Estimate the depth at which the boron concentration is 1% of the initial surface concentration.

For the diffusion of boron in silicon, the activation energy E is 3.5 eV and the corresponding pre-exponential factor D_o is 3.7×10^{-2} cm^{2}s^{-1}.   [7]

END OF PAPER