ENGINEERING TRIPOS PART IB

Tuesday 5 June 2007 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.

There are no attachments to this paper.

STATIONERY REQUIREMENTS
Single-sided script paper

SPECIAL REQUIREMENTS
Engineering Data Book
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

SECTION A

1 Consider the slow cooling to room temperature of the following metallic alloys:

(i) a medium carbon steel, Fe-0.4 wt.% C, cooled from 850 °C;

(ii) an aluminium casting alloy, Al-12 wt.% Si, cooled from 600 °C.

In each case:

(a) Describe the stages in the evolution of the microstructure, noting the key temperatures and phase transformations. Illustrate your answers with sketches of the relevant phase diagrams, indicating salient features that determine the microstructure evolution, including the phase compositions. [8]

(b) Sketch the final microstructures, and summarise how the mechanism of each phase transformation influences the size and morphology of the final phases. [8]

(c) Suggest an application for the alloy, and comment on whether it would be processed in this way in practice. [4]

2 (a) Explain carefully the phenomena of homogeneous and heterogeneous nucleation in metals processing. Give examples of heterogeneous nucleation to support your answer. [5]

(b) A solid phase α lies on a flat substrate S. A new phase β nucleates from the α phase at the interface with the substrate. The β phase forms as a thin, circular disc of fixed thickness h and increasing radius r, as shown in Fig. 1. $\Delta G_{\alpha\beta}$ is the difference in Gibbs free energy per unit volume between phases α and β. The surface energies per unit area of the α/β, α/S and β/S interfaces are $\gamma_{\alpha\beta}$, $\gamma_{\alpha S}$ and $\gamma_{\beta S}$, respectively.

(i) Obtain an expression for the change in surface energy per unit area due to the formation of the β phase nucleus.

(ii) Obtain an expression for the change in free energy ΔG_{tot} for nucleation of the β phase in terms of r and h.

(iii) Hence show that the critical radius r^* for heterogeneous nucleation for the β phase in Fig. 1 is given by

$$r^* = \frac{-h\,\gamma_{\alpha\beta}}{\gamma_{\alpha\beta} + \gamma_{\beta S} - \gamma_{\alpha S} + h\Delta G_{\alpha\beta}} \,.$$ [10]

(c) Discuss the factors that determine the rate of grain nucleation in solids. [5]

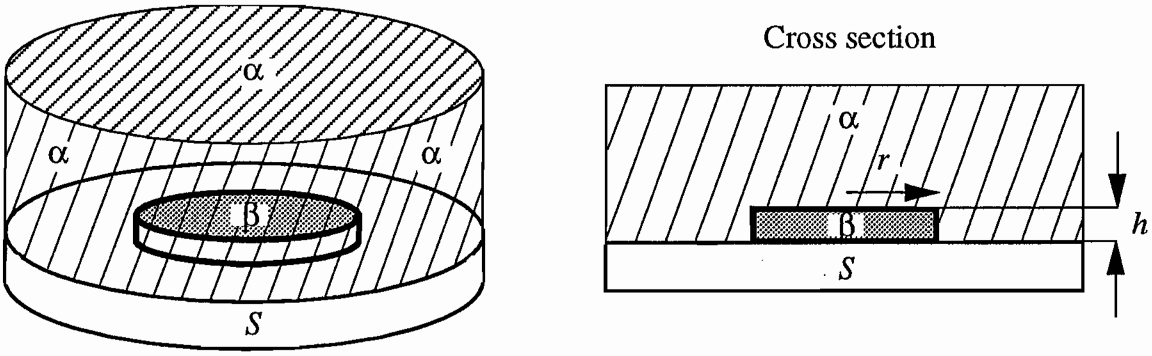

Fig. 1

(TURN OVER

3 (a) Explain carefully why freshly-drawn glass fibres can have a tensile strength many times that of fibres that have been handled and exposed to the atmosphere. How is the strength of optical glass fibres maintained at a high level during use in practical applications? [5]

(b) The ends of a long bar of elastic material are constrained at a fixed distance apart. The bar is then exposed to a uniform temperature rise of ΔT. Show that the magnitude of the longitudinal stress σ in the bar is given by $\sigma = E\,\alpha\,\Delta T$, where E is Young's modulus and α is the coefficient of thermal expansion of the bar material. State whether the stress is tensile or compressive. [5]

(c) Describe the process of *thermal toughening*, as used for the glass in car side windows. How is the mechanical behaviour of the glass modified by such treatment? Explain how the value of stress derived in (b) can be used to estimate the stress in the surface of a thermally toughened glass sheet. What factors might influence the value of ΔT in this application?

Give one reason why thermal toughening cannot be applied successfully to thermoplastic polymers. [6]

(d) A car window is made from soda-lime glass, and contains surface scratches to a maximum depth of 100 μm. Estimate the tensile strength of the glass if it is thermally toughened. How does this compare with the tensile strength of glass that has not been thermally toughened? [4]

For soda-lime glass, $\alpha = 9 \times 10^{-6}$ K^{-1}, E = 70 GPa and fracture toughness K_{IC} = 0.6 MPa m$^{1/2}$. You may assume that ΔT = 300 K for the thermal toughening process.

SECTION B

4 (a) Describe briefly four examples of material properties that are important in determining the processibility of engineering materials. In each case, give examples of the relevant processes and materials. [6]

(b) Explain how grain size may be modified during solid state forming. Your answer should describe the process steps, key process variables and the mechanisms of microstructural change. [4]

(c) Explain briefly what is meant by inter-phase coherency. Why is it important in the age hardening of aluminium alloys? [6]

(d) Compare the age hardening of heat-treatable aluminium alloys with the quenching and tempering of hardenable steels. What are the essential similarities between the two processes, and in what important respects do they differ? [4]

(TURN OVER

5 (a) Describe the difference in microstructure between amorphous and partially-crystalline polymers. Explain qualitatively how the elastic modulus of a bulk polymer depends on the extent of its crystallinity and molecular alignment. [5]

(b) Describe the following processes for the manufacture of containers from a thermoplastic polymer:

(i) rotational moulding;
(ii) blow moulding;
(iii) stretch blow moulding.

Explain clearly the differences between these processes and between the structures and properties of the resulting products. What advantages does a stretch blow moulded bottle have over a blow moulded bottle for containing a carbonated fizzy drink? [6]

(c) A bottle for a carbonated drink can be treated as a cylindrical, thin-walled pressure vessel with a diameter of 60 mm and a wall thickness of 0.3 mm. The internal pressure in the bottle is 0.4 MPa. Calculate the hoop and longitudinal stresses in the wall of the bottle. Hence determine the minimum yield stresses required for the wall material in these directions, assuming a safety factor of 2.5. [4]

(d) It is proposed to manufacture the bottle by stretch blow moulding in PET (polyethylene terephthalate) for which, in amorphous form, the yield stress is 50 MPa. Explain the roles of crystallisation and molecular alignment in achieving the required polymer properties. Suggest, explaining your reasons, approximate temperatures at which the various stages of the manufacturing process should be carried out. [5]

For PET, the glass transition temperature T_g is 85 °C and the crystalline melting temperature T_m is 250 °C.

6 A prototype manufacturing route for a Ni-Cu alloy is to diffusion bond togcthcr alternate layers of pure Cu and of a Cu-Ni alloy containing 20 atomic % Ni. Assume that each layer is of uniform thickness h , the through-thickness co-ordinate is represented by x , and C is the concentration of Ni (atomic %) in Cu, as shown in Fig. 2.

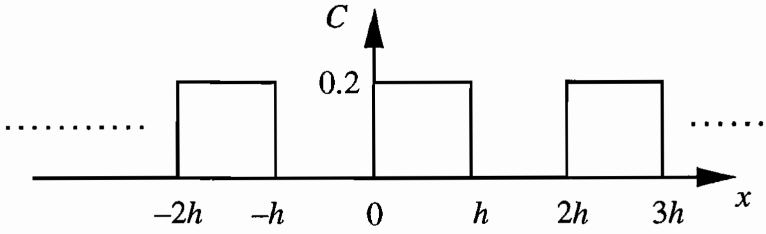

Fig. 2

(a) By considering the Fourier series given on page 17 of the Mathematics Data Book for the 'General Range', justify that the initial concentration profile $C(x, t=0)$ can be written as

$$C(x, t=0) = 0.1 + \sum_{n=1,3,5,..}^{\infty} \frac{0.4}{\pi n} \sin\left(\frac{\pi n x}{h}\right) .$$

Note that it is only necessary to determine a general expression for the Fourier coefficients, and that detailed numerical calculations to extract individual values are not required. [6]

(b) The transient solution for $C(x, t \geq 0)$ is obtained by pre-multiplying each term of the Fourier series in (a) by a function of time $g_n(t)$. Using the Materials Data Book, show that the first two terms of the transient solution are

$$C(x, t \geq 0) = 0.1 + \exp\left[-\frac{t}{\tau_1}\right] \frac{0.4}{\pi} \sin\left(\frac{\pi x}{h}\right) .$$

Find an expression for the time constant τ_1 and explain its physical significance. [8]

(c) Determine whether a one hour heat treatment at 1000 °C is sufficient to homogenise the alloy for alternating Cu and Cu-Ni layers of thickness 1 μm. For the diffusion of Ni in Cu, the diffusion constant $D_0 = 2.0 \times 10^{-4}$ m^{2}s^{-1} and the activation energy $Q = 280$ kJ mol^{-1}. [6]

END OF PAPER