ENGINEERING TRIPOS PART IB

Tuesday 7 June 2005 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.

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

(TURN OVER

SECTION A

1 (a) Describe the procedure and purpose of a Jominy end-quench test. [4]

(b) A Jominy bar is quenched from an initial uniform temperature T_1 to an ambient temperature T_0. The cooling rate $\mathrm{d}T/\mathrm{d}t$ at a temperature T varies with distance x from the quenched end of the bar according to

$$\frac{\mathrm{d}T}{\mathrm{d}t} \approx -\frac{AB^2}{\sqrt{\pi}}\left(\frac{4a}{x^2}\right)\exp\left(-B^2\right)$$

where $A = (T - T_0)$, $B = (T - T_0)/(T_1 - T_0)$ and a is the thermal diffusivity. This approximate solution is valid for $B < 0.7$.

When a large slab of thickness $2l$ is quenched between the same initial and ambient temperatures as those of the Jominy bar, the temperature history $T(t)$ at mid-thickness is given by

$$\frac{T(t) - T_0}{T_1 - T_0} = \frac{4}{\pi}\left[\exp\left(-\frac{\pi^2 at}{4l^2}\right)\right]$$

(i) Find an expression for the cooling rate $\mathrm{d}T/\mathrm{d}t$ at the centre of the slab, in terms of $A = (T - T_0)$, l and a. [4]

(ii) Hence show that a position 5.1 mm along a Jominy bar has the same cooling rate as that at the centre of a slab of thickness 24 mm, for a temperature halfway between T_1 and T_0. [4]

(iii) Use the Jominy end-quench curves in the Materials Databook to find the as-quenched hardness at the centre of 24 mm thick slabs of steels BS503M40 and BS817M40. Select a tempering temperature for each steel to give a maximum Vickers hardness at the centre of 300 kgf/mm^2. [4]

(iv) Account for the changes in hardness produced on tempering following a rapid quench in these steels. Explain which of the two steels is expected to be more weldable. [4]

2 An automotive engine component is to be manufactured from a heat-treatable Al-Mg-Si alloy. The component is forged at 300 °C and then undergoes a separate heat treatment.

(a) Outline a suitable heat treatment schedule for this class of alloy, to maximise the yield strength. Summarise the main microstructural changes that occur during heat treatment. Explain why forging is undertaken at 300 °C, and why it is not possible for the forging step to serve also as the first stage in the heat treatment. [7]

(b) In what respects might the process history change if the alloy is replaced by a non-heat-treatable Al-Mg alloy, if a comparable final strength is required? [3]

(c) For both the heat-treatable and non-heat-treatable Al alloys, comment on possible problems associated with:

(i) arc welding of the component during assembly;

(ii) prolonged exposure of the component to a temperature of 100 °C during service. [4]

(d) The component has a mass of approximately 0.05 kg, a minimum thickness of 6 mm and a required tolerance of 0.1 mm. Production runs over 50,000 are expected. Discuss the implications for the manufacture of the component by forging. Reference may be made to the process attribute charts in the Materials Databook. Suggest an alternative processing route, and comment on any influence that this alternative route may have on the mechanical properties of the component. [6]

3 (a) Briefly summarise the potential benefits of a process model for a deformation process such as forging. [4]

(b) An experimental plane strain forging process is illustrated in Fig. 1. A long rectangular billet of cross-section $2h \times w$ is forged between two platens A and B as shown. Lateral motion of one side of the billet is prevented by the rigid block C. The frictional shear stress $\tau(x)$ between the platens and the billet is described by a friction factor m, such that $\tau(x) = mk$, where k is the shear yield stress of the material.

(i) By considering the horizontal equilibrium of the element shown in Fig. 1, show that

$$\frac{\mathrm{d}\sigma_x}{\mathrm{d}x} = -\frac{mk}{h}$$

[4]

(ii) Hence use the Tresca yield criterion to obtain an expression for the pressure gradient, $\mathrm{d}p/\mathrm{d}x$. Show that the pressure distribution is given by

$$p(x) = \sigma_y\left(1 + \frac{m}{2}\left(\frac{w-x}{h}\right)\right)$$

[6]

(iii) Find expressions for the net forging load per unit length P and the transverse restraining force per unit length F imposed by the rigid block C upon the billet. [6]

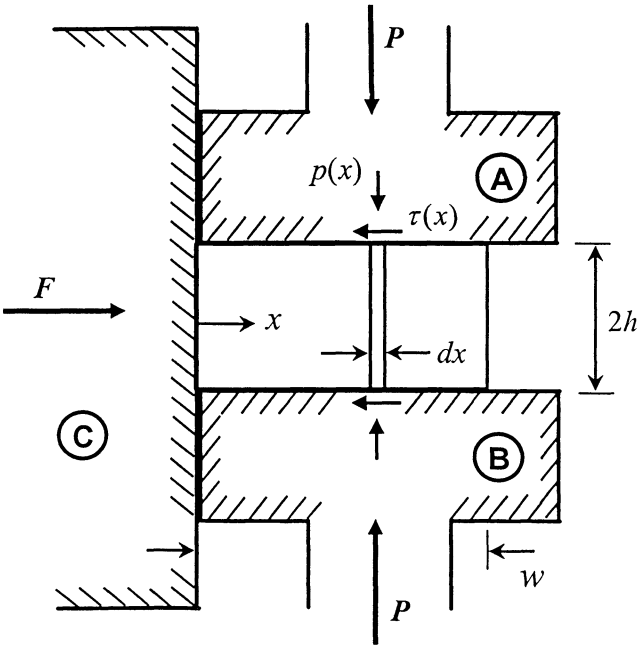

Fig. 1

SECTION B

4 (a) Briefly explain the purpose of the following processes in microelectronics fabrication:

(i) distillation of $SiHCl_3$ and reaction with hydrogen;

(ii) Czochralski solidification;

(iii) oxidation of silicon. [6]

(b) (i) Distinguish between the pre-deposition and drive-in stages in the doping of silicon.

(ii) Pre-deposition of boron was conducted at 1000 °C for 10 minutes. Estimate the minimum temperature needed for a drive-in stage lasting one hour, if the characteristic diffusion distance must be at least ten times the distance achieved during pre-deposition. [For B in Si, the diffusion constant $D_o = 3.7 \times 10^{-6}\ \mathrm{m^2\,s^{-1}}$ and the activation energy $Q = 333\ \mathrm{kJ\,mol^{-1}}$.] [8]

(c) The oxidation of silicon may be described by the Deal-Grove equation:

$$y^2 + Ay = Bt$$

where y is the oxide thickness after time t, and A, B are constants, with values of 0.09 μm and $7.50 \times 10^{-18}\ \mathrm{m^2\,s^{-1}}$ respectively at 1100 °C.

Find:

(i) the time required to grow a layer of thickness 150 nm;

(ii) the thickness of oxide formed in 90 minutes;

(iii) the ratio of the times taken to form the first and second halves of the full layer thickness in (ii). [6]

(TURN OVER

5 A deformation mechanism map for pure Ni is shown in Fig. 2. The contours are lines of equal strain-rate for steady-state creep, in units of s^{-1}.

(a) For each of the two mechanisms of creep, explain briefly the physical basis for the subdivision into two regimes. [4]

(b) For a constant temperature of 800 °C, plot the variation of strain-rate $\dot{\varepsilon}$ with stress, on log scales. Hence estimate the stress exponent n for each of the two mechanisms of creep in this alloy. Outline how a similar cross-plot of data from the map can be used to find the activation energy for creep. [6]

(c) A component is to be made from pure Ni in the condition given in the map of Fig. 2. It is intended to operate the component at a stress of 2 MPa and a temperature of 600 °C. Use the map to comment on the wisdom of evaluating the creep life in service by extrapolation from tests on the material at stresses between 10 and 50 MPa, with temperatures between 800 and 1000 °C. [4]

(d) Explain why Ni superalloy MAR-M200 has a superior creep resistance to pure Ni. Illustrate your answer with sketches of deformation maps for:

(i) pure Ni, as in Figure 2;

(ii) superalloy MAR-M200 with the same grain size as the pure Ni;

(iii) superalloy MAR-M200 with a grain size 1000 times greater.

Your sketches should show the boundaries of the main creep mechanisms, and the extreme strain-rate contours (10^{-10} and 1 s^{-1}). [6]

(cont.

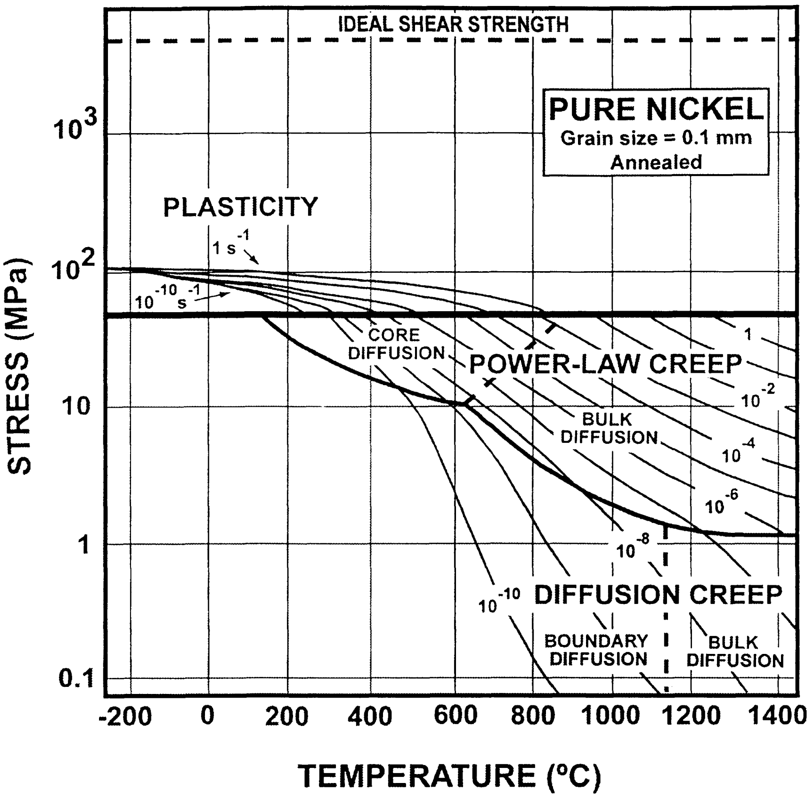

Fig. 2

6 (a) Use the phase diagrams in the Materials Databook to find the chemical formulae of the following single phase compounds:

(i) θ in Aluminium-Copper;

(ii) ε in Copper-Tin;

(iii) Mullite in Silica-Alumina. [6]

(b) A Pb-Sn alloy containing 40 wt% Sn is cooled slowly from the melt to room temperature. Describe with sketches the evolution of the microstructure, noting salient temperatures and phase compositions. In what main respects might the behaviour of a Pb-80 wt% Sn alloy differ? [10]

(c) A Cu-50 wt% Ni alloy is solidified at a moderately fast cooling rate. Sketch the likely variation in composition across a representative grain in the solidified microstructure, and explain the cause of the variation. [4]

END OF PAPER

Correction to Engineering Tripos Part IB
Paper 3 – Materials
Tuesday June 7th 9-11

Q.4 (c) Value of constant B should be $7.50 \times 10^{-18}\ \mathrm{m}^2\ \mathrm{s}^{-1}$, not $9.72 \times 10^{-11}\ \mathrm{m}^2\ \mathrm{s}^{-1}$

Correction to Engineering Tripos Part IB, Paper 3 – Materials
Tuesday June 7th 9-11

Q.4 (c) Value of constant B should be 7.50×10^{-18} m^2 s^{-1}, not 9.72×10^{-11} m^2 s^{-1}

Dr Hugh Shercliff
Examiner