UNIVERSITY OF
CAMBRIDGE

ENGINEERING TRIPOS PART IB

Tuesday 1 June 2004 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 process of producing a high combined hardness and toughness in medium carbon steels. Explain why this process is not used for low carbon steels. [6]

(b) Figure 1 shows the isothermal transformation diagram for a 0.45 wt. % plain carbon steel. Identify the microstructures labelled A to E on this figure and describe briefly the process conditions under which they form. State which of these are phases. Hence determine the time-temperature heat treatments required to produce the following final microstructures in a small specimen of this steel:

(i) 100% martensite;
(ii) 100% bainite;
(iii) 75% bainite and 25% martensite;
(iv) 10% ferrite and 90% fine pearlite.

Assume that the specimen is heated initially to 845 °C and held at this temperature for 1 hour prior to each heat treatment. [10]

(c) Describe the displacive structural transition that takes place when martensite forms from austenite in plain carbon steels. Why doesn't martensite appear in the iron-carbon phase diagram? [4]

(cont.

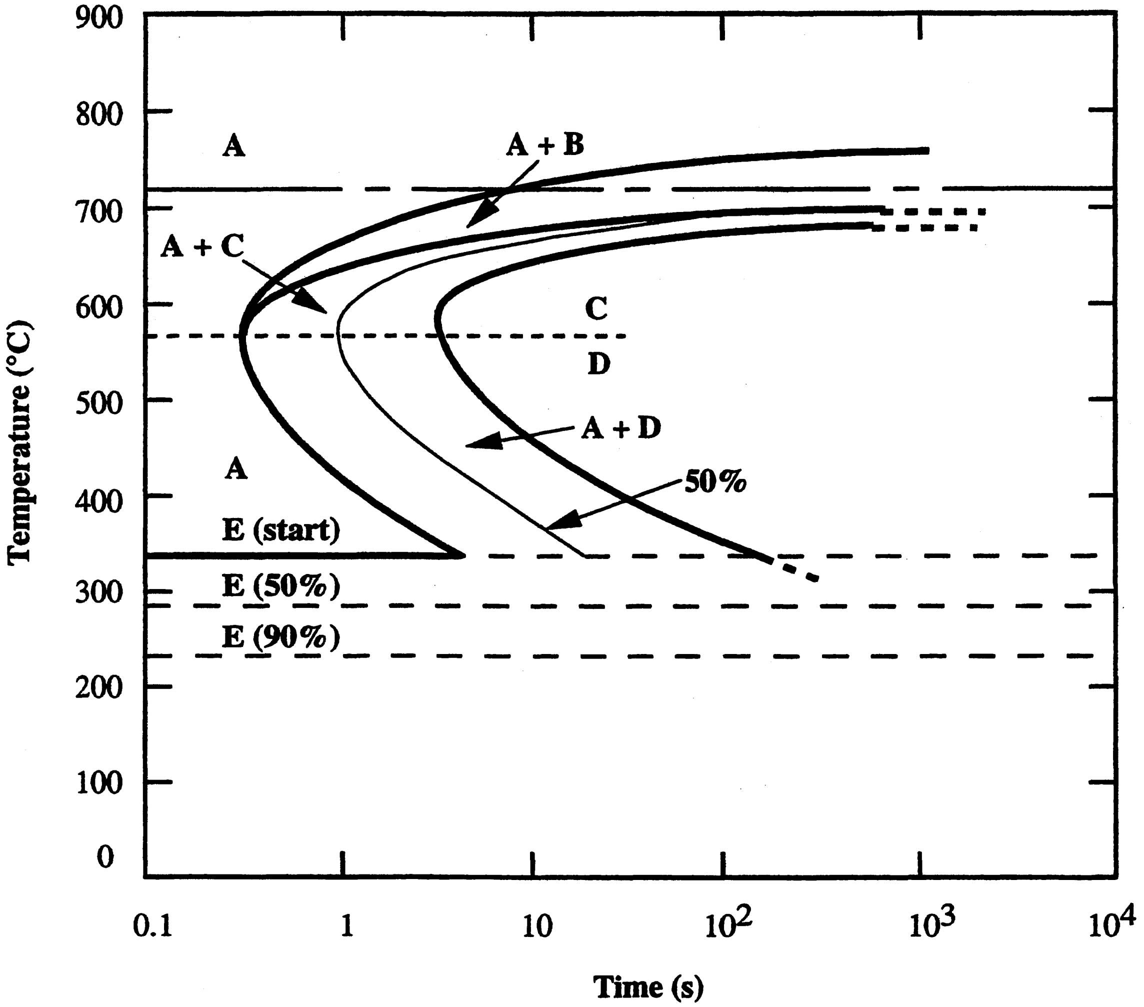
900
800
700
600
500
400
300
200
100
0
Temperature (°C)
0.1
1
10
10^2
10^3
10^4
Time (s)
A
A + B
A + C
C
D
A + D
50%
A
E (start)
E (50%)
E (90%)

Fig. 1

2 (a) Describe the physical basis of, and conditions under which, a metal alloy will deform by:

(i) power law creep;

(ii) diffusional creep. [6]

(b) The measured steady-state strain rate, $\dot{\varepsilon}$, as a function of temperature for a nickel-based alloy of density $\rho = 8{,}900$ kg m^{-3} under a constant tensile stress σ of 6 MPa is given in Table 1. The behaviour of the alloy can be described by the diffusional creep equation

$$\dot{\varepsilon} = A\sigma \exp\left[-\frac{Q}{\mathrm{R}T}\right]$$

where A is a constant, Q is the activation energy, R is the gas constant and T is the absolute temperature. Construct an Arrhenius plot of the data in Table 1. Hence estimate the value of Q for this alloy. [6]

(c) The nickel-based alloy is to be used as a turbine blade of root radius r_r and tip radius r_t of 0.2 m and 0.25 m, respectively, as illustrated schematically in cross-section in Fig. 2. Show that the strain rate in the blade rotating with angular velocity ω at a position r from the centre of the turbine is given by

$$\dot{\varepsilon} = A\frac{\rho\,\omega^2}{2} \exp\left[-\frac{Q}{\mathrm{R}T}\right]\left(r_t^2 - r^2\right).$$

If the turbine blade operates at a temperature of 600 °C and a rotational speed of 10,000 rpm, determine the length change in the blade after continuous operation for 100 hours. [8]

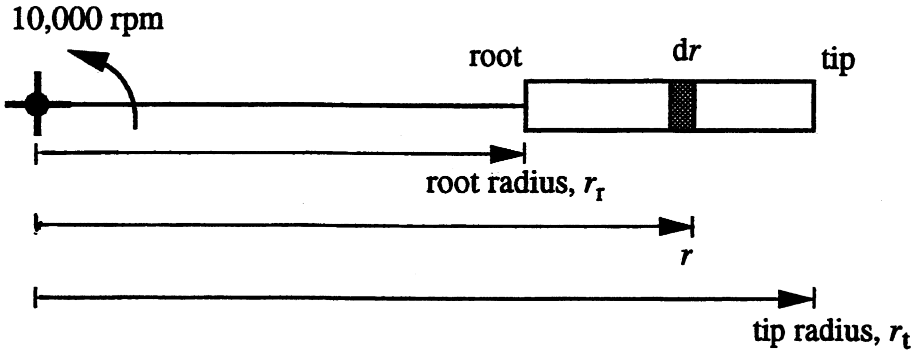

Fig. 2

Strain Rate $\times 10^{-10}$ s^{-1}	Temperature ^{o}C
2	600
4	650
8	700
14	750
25	800
42	850

Table 1

3 (a) Describe carefully the following processes:

- (i) extrusion of polymers;
- (ii) float glass technique;
- (iii) hot isostatic pressing of ceramics.

Explain any significant properties or characteristics of materials produced by the above techniques. [9]

(b) Explain carefully how the strength of polymers, glasses and ceramics can be improved by processing. [5]

(c) A tie bar of circular cross-sectional area, length L and diameter d, where $d << L$, in the viewing window of a low pressure system is to be manufactured from either soda-lime glass, silica or borosilicate glass. The ends of the bar are fixed and are well-insulated. The section through the bar is illustrated in Fig. 3. Derive an approximate expression for the maximum allowable temperature decrease of the bar, ΔT, as a function of the failure stress of the bar, σ_f, the coefficient of thermal expansion, α, and Young's modulus, E, assuming that the bar is initially in a state of zero stress.

In practice the temperature of the bar on cooling can change by up to 400 °C. Hence identify which of the candidate glasses is most suitable for this application, stating any assumptions you make. The relevant material parameters are given in Table 2.

How would the calculation differ if the temperature of the bar were to increase, rather than decrease? [6]

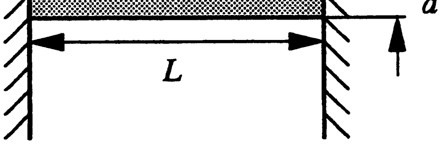

Fig. 3

Glass	$\alpha \times 10^{-6}$ K^{-1}	E GPa	σ_f MPa
Soda-lime	9	70	33
Silica	0.5	71	80
Borosilicate	4	63	27

Table 2

SECTION B

4 (a) What is a *phase diagram* and what is meant by the *lever rule* ?

Sketch the arrangement of lines on a phase diagram that would indicate the following:

(i) a eutectic;
(ii) a eutectoid;
(iii) a peritectic;
(iv) a peritectoid;
(v) an intermetallic compound.

Label clearly the phases on your sketches, with the solid phases represented as α, β, γ etc.

Sketch a phase diagram for two materials that are mutually soluble in each other at all concentrations. [10]

(b) Figure 4 shows schematically the microstructure of a binary Pb-Sn alloy at room temperature. Use the phase diagram in the Materials Data Book (Fig. 6.2) to estimate the composition of the alloy. Explain the details of the microstructure and describe the conditions under which the sample was cooled, giving reasons for your answer.

Describe the evolution of the microstructure in Fig. 4 as the sample is cooled from a liquid state, using sketches to illustrate your answer. [10]

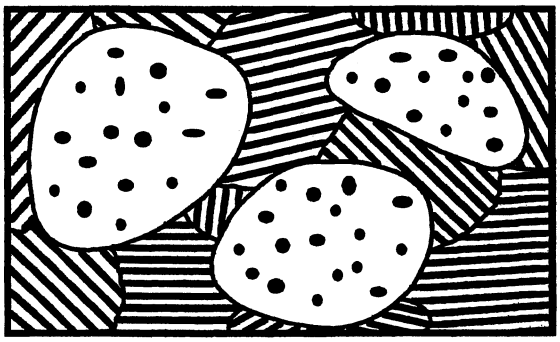

Fig. 4

5 (a) Explain the physical basis of the Arrhenius temperature dependence of diffusion. List the factors that determine how rapidly one material diffuses into another. [4]

(b) Explain how diffusion-controlled processes can be used to optimise the properties of:

(i) heat-treatable aluminium alloys;
(ii) non heat-treatable aluminium alloys;
(iii) semiconductors. [6]

(c) A carbon steel bearing is to be case-carburised at elevated temperature from an initial uniform concentration C_0. The concentration C of carbon in the steel that has diffused in from the surface is given by

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

where C_s is the constant concentration at the surface, x is the distance from the surface, t is the time and D is the diffusion coefficient.

Sketch the concentration as a function of distance from the surface at a given carburising time, t. Include in your sketch an indication of how the concentration profile varies with time.

The carbon steel bearing has an initial carbon content of 0.2 wt. %. The surface carbon concentration of the steel at elevated temperature is maintained at 0.9 wt. % in the carburising process. After 1 hour at 900 °C the concentration at 0.2 mm from the surface is 0.6 wt. %. When the process is repeated on the same steel at 1,000 °C, the concentration after 1 hour at 0.2 mm from the surface is 0.7 wt. %. Determine the activation energy for the diffusion of carbon in steel. [10]

6 (a) List the main *process attributes* that define the physical capabilities of a process. [2]

(b) A process is required for the production of 10,000 crankshafts for car engines. The crankshaft is a complex three-dimensional shape about 0.3 m in length with a minimum diameter of about 0.06 m. The crankshaft must be stiff, tolerate moderately high temperatures, be resistant to fatigue and have a high yield stress without being too brittle. At the position of the bearings, the surface of the crankshaft must be very hard, have a finish better than 1 μm and a dimensional accuracy of ± 0.1 mm. Other parts of the crankshaft can be rough.

Suggest possible materials for the crankshaft and identify a suitable fabrication route that meets all of the above design requirements, explaining carefully the reasons for your selection. [12]

(c) Describe a simple cost model for batch shaping processes. Define the parameters in the model and sketch how the cost per unit part varies with the batch size. Show how the cost model helps to identify the likely economic batch size for two competing processes. [6]

END OF PAPER