Version HRS/3

EGT1
ENGINEERING TRIPOS PART IB

Tuesday 2 June 2015 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 The equilibrium phase diagram for SiO_2 and Al_2O_3 is shown in Fig.1a.

(a) (i) The phase diagram contains a number of reactions in which the phases change completely at constant temperature. In each case, identify the reaction type, composition and temperature, and state the phases involved. [6]

(ii) For a 50:50wt% mixture of SiO_2 and Al_2O_3 find the proportions and compositions of the phases present at 1800 °C, showing your working. [5]

(iii) On a plot of the Gibbs free energy *G* against wt% Al_2O_3 sketch the variation of *G* with composition for the phases present at 2100 °C, and at 1800 °C. On your sketch, mark the variation of minimum total Gibbs free energy with wt% Al_2O_3, indicating salient values of the composition. [6]

(b) Figure 1b shows a schematic micrograph of a 73 wt% Al_2O_3 sample which has been heated to 2000 °C for a long period and then cooled to 1750 °C and left for 30 days, followed by rapid cooling to room temperature. The regions labelled are: A, alumina; G, an amorphous glass phase; and M, mullite.

(i) Has the sample reached equilibrium? Explain your reasoning, and outline the solidification sequence that led to the microstructure shown. [6]

(ii) Suggest a processing technique that would enable the growth of a single crystal of mullite. [2]

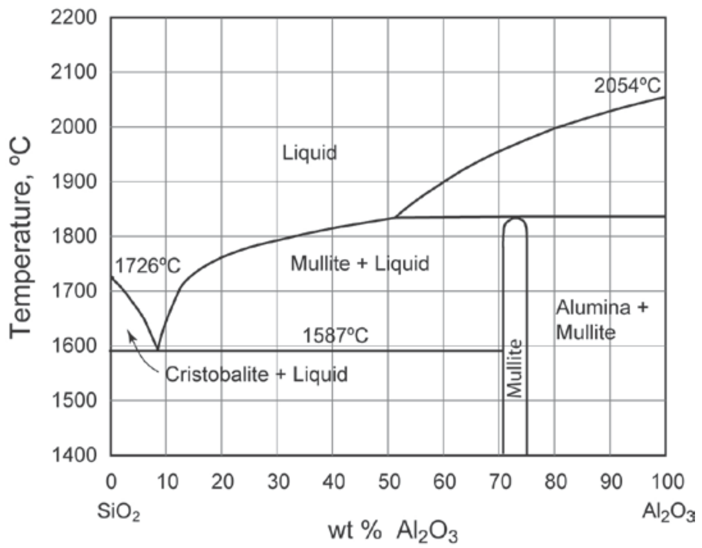

Fig.1a

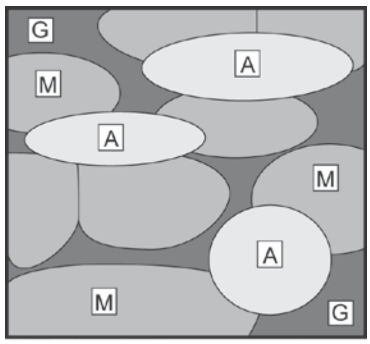

Fig. 1b

2 (a) (i) A 0.4 wt% carbon steel was held at a temperature of 850 °C and then cooled slowly to room temperature. Sketch and label the microstructures expected at 850 °C, at 730 °C, and at room temperature. [6]

(ii) Sketch and name the microstructure expected if the steel was cooled very rapidly to room temperature. Briefly describe the mechanism by which it forms. [4]

(b) Cylindrical bars with a wide range of diameters were manufactured in a plain carbon steel and a low alloy steel, both containing 0.4 wt% C. The bars were heated to 850 °C, and then quenched in water to room temperature. After sectioning, the hardness at the centre of each bar was measured.

Sketch the expected form of a graph showing hardness against bar diameter, for both steels. Define the term *hardenability* and indicate a suitable measure of this quantity on your graph. Explain how the alloying additions influence the hardenability of the low alloy steel, and suggest suitable alloying elements. [8]

(c) (i) Explain the purpose of *tempering* after quenching a carbon or alloy steel. Sketch the variation of hardness with tempering time. [3]

(ii) A number of aluminium alloys are also heat treated by holding at high temperature, followed by quenching and ageing. Briefly outline two ways in which this process is metallurgically analogous to the quenching and tempering of steels, and two ways in which it is significantly different. [4]

3 (a) (i) Sketch a stress-strain response for a *viscoelastic* material under cyclic loading with zero mean stress. How does the response differ from that of a purely *elastic* material? [4]

(ii) The Young's modulus for a viscoelastic material may be represented by a real and an imaginary component. Sketch how these components vary with temperature for a typical thermoplastic, and explain how this may be used to identify the glass transition temperature. [6]

(b) Viscoelastic materials can be modelled using *spring* and *dashpot* elements, with modulus E and viscosity η. For both of the systems shown in Fig. 2a, write down the governing differential equation and sketch, without calculation, the expected strain response when subjected to a step increase in stress. [6]

(c) The rubber for a suspension element from a road vehicle is modelled using the arrangement of springs and dashpots shown in Fig. 2b.

(i) Derive the governing differential equation for this arrangement. Sketch, without calculation, the strain response to a step increase in stress. [7]

(ii) Without further calculation, explain which elements in the system would have most influence on the cyclic response at low frequency, and at high frequency. [2]

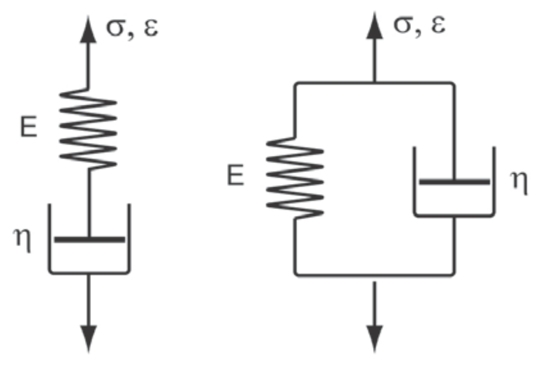

Fig. 2a

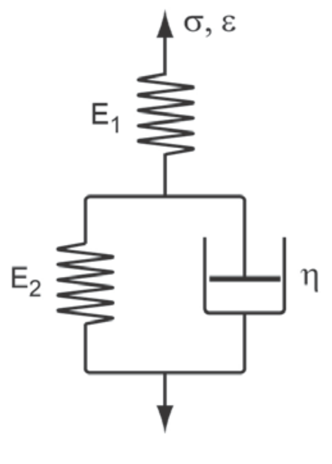

Fig. 2b

SECTION B

4 (a) In the Jominy end-quench test, a circular bar of steel is held in a furnace until it has a uniform temperature T_1 = 1000 °C, and is then quenched on one end with a water jet at a temperature T_0 = 20 °C. Assuming heat transfer to the water is perfect, the solution for the temperature T at a distance x and time t is given by

$$\frac{T(x,t) - T_0}{T_1 - T_0} = \operatorname{erf}\left(\frac{x}{2\sqrt{a\,t}}\right)$$

where a is the thermal diffusivity of the steel, and $\operatorname{erf}(X)$ is the error function.

(i) Briefly outline the purpose of the Jominy end-quench test. [3]

(ii) Using the approximation $\operatorname{erf}(X) \approx X$ (for $X < 0.7$) derive an expression for the time taken to cool to a specified temperature T at a given distance from the end of the bar. Over what temperature range is this approximation valid? [5]

(iii) As an indicator of cooling rate, it is proposed to use the time taken to cool through the fixed temperature interval between 700 °C and 400 °C. Using your expression in part (ii) above, write down an expression for the average cooling rate in this interval. [4]

(iv) When a large plate of thickness 2w is quenched from a uniform temperature T_1 into water at a temperature T_0 the temperature at mid-thickness, after an initial transient period, is given by

$$\frac{T(x,t) - T_0}{T_1 - T_0} = \frac{4}{\pi} \exp\left(-\frac{\pi^2 a\,t}{4\,w^2}\right)$$

Derive a corresponding equation for the average cooling rate at mid-thickness through the temperature interval between 700 °C and 400 °C, for the same initial and water temperatures, T_1 and T_0. Hence derive a relationship between the thickness of the plate, 2w, and the distance from the quenched end of a Jominy bar, x_J, that have the same cooling rate in this interval. [7]

(b) The error function solution is also found in a number of problems of atomic diffusion in materials processing. Give one example process, sketching the boundary conditions and form of the solution. Explain how the equation in part (a) is adapted to give a solution to this problem. Briefly explain the purpose of your chosen process. [6]

 (TURN OVER

5 (a) Figure 3 shows a deformation mechanism map for a commercial purity Ni alloy.

(i) The variation of strain-rate $\dot{\varepsilon}$ with stress σ and temperature T is to be fitted to an equation of the form

$$\dot{\varepsilon} = A\,\sigma^{n}\exp(-Q/RT)$$

where Q is the activation energy for creep, and R is the universal gas constant.

Plot a suitable graph at a constant temperature T = 800 °C to estimate values of n for power law creep and for diffusional flow. Show your working. [6]

(ii) Without further analysis, describe how you would estimate a value for the activation energy for creep. [3]

(iii) A component made from this Ni alloy is to be operated at a design stress of 0.8 MPa and a temperature of 800 °C, but the designer does not have access to the mechanism map. To accelerate trials during prototyping, a test programme is proposed at stresses between 10 and 30 MPa, at the design temperature. Estimate the strain-rate that these tests will predict at the design stress, explaining your working. Comment on the advisability of conducting the test programme, and suggest an alternative means of obtaining acceptable data in an accelerated test programme. [5]

(iv) The component is to be hot forged during manufacture at a temperature of 1200 °C. The billet initially has a square cross-section 10×10 cm, and the maximum descent speed of the press is 1 mm s^{-1}. Estimate the initial forging stress using the deformation mechanism map. Explain why, in practice, the applied forging pressure is likely to be considerably higher than this. [5]

(b) Turbine blades for jet engines are manufactured using Ni-based superalloys. Explain how the composition and processing route are modified to provide resistance to both power law creep and diffusional flow. [6]

 (cont.

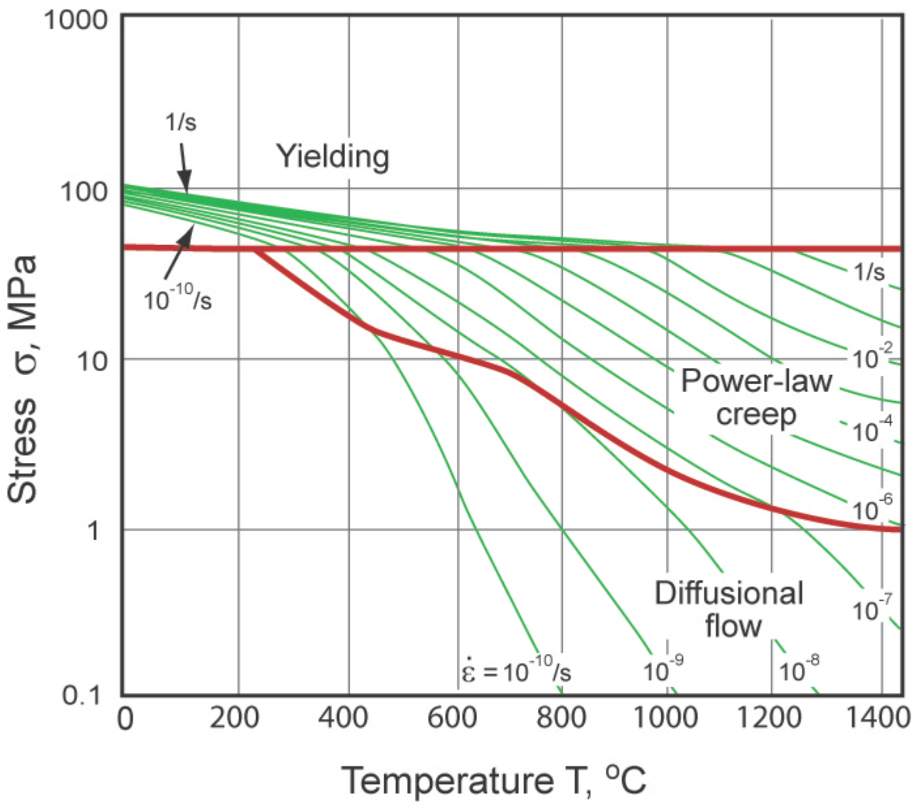
1000
100
10
1
0.1
Stress σ, MPa
0
200
400
600
800
1000
1200
1400
Temperature T, °C
Yielding
1/s
10^-10/s
1/s
10^-2
Power-law creep
10^-4
10^-6
10^-7
Diffusional flow
ε̇ = 10^-10/s
10^-9
10^-8

Fig. 3

6 (a) (i) The onset of solidification of a liquid may be analysed by considering the homogeneous nucleation and growth of a solid sphere within the liquid. Write down an expression for the change in the total free energy ΔG_{tot} after formation of a sphere of radius r, defining the meaning of all the terms. Using a sketch of this expression, explain why there is a critical radius for stability of the solid nucleus. [6]

(ii) In practical casting heterogeneous nucleation is likely to occur instead. Give examples of nucleation sites, and state what microstructural characteristics of the casting are most strongly affected by this nucleation. [3]

(b) Briefly outline, with sketches as appropriate, the nucleation and growth mechanisms in recrystallization of an Al alloy after cold rolling. [5]

(c) A material in equilibrium at a high temperature is cooled quickly to below the equilibrium temperature for a diffusional phase transformation to occur, and held isothermally. The extent of the phase transformation may be characterised by a *TTT diagram*.

(i) Sketch a typical TTT diagram, showing its characteristic shape. Explain briefly how two temperature-dependent factors govern this shape. [6]

(ii) Now consider the reverse process of rapidly heating a material in equilibrium below the transformation temperature, and holding it isothermally above that temperature. Would you expect the same characteristic shape of TTT diagram? Explain your reasoning. [2]

(iii) Outline, with sketches, an example of a TTT diagram in the processing of thermoplastics. [3]

END OF PAPER

ENGINEERING TRIPOS PART IB **JUNE 2015**
PAPER 3: MATERIALS

Answers

1. (a) (ii) 55% Liquid (~33 wt% Al_2O_3), 45% Mullite (~71 wt% Al_2O_3).

3. (c) (i) $\eta\,\dot{\sigma} + (E_1 + E_2)\sigma = E_1\,E_2\,\varepsilon_1 + \eta\,E_1\,\dot{\varepsilon}_1$

4. (a) (ii) 20°C < T < 706°C

(a) (iii) Average cooling rate between 700 and 400°C: $\approx 262\left(\dfrac{a}{x^2}\right)$

(a) (iv) Average cooling rate between 700 and 400°C: $\approx 5088\left(\dfrac{a}{(2w)^2}\right)$

$(2w) \approx 4.40\ X_{\mathrm{J}}$

5. (a) (i) Diffusional flow: n ≈ 1; power-law creep: n ≈ 4.2.

(a) (iv) Forging stress ≈ 18 MPa.