ENGINEERING TRIPOS PART IB

Tuesday 4 June 2013 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.

STATIONERY REQUIREMENTS
Single-sided script paper
Graph paper
Log-Log graph 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 (a) Most commercial creep-resistant metals operate in the dislocation creep regime. Explain the mechanism responsible for dislocation creep in metals. How would you choose a material to reduce deformation by dislocation creep? Explain your reasoning. Give an example of an engineering material in which this type of creep is suppressed. [7]

(b) The steady-state creep rate $\dot{\varepsilon}_{\mathrm{ss}}$ varies with applied stress σ and temperature T according to the following equation

$$\dot{\varepsilon}_{\mathrm{ss}} = A\sigma^{n}\exp\left(-\frac{Q}{RT}\right)$$

where A and n are constants, Q is the activation energy for creep and R is the gas constant.

Table I shows creep rupture data related to 316 austenitic stainless steel. Assuming that the rupture life is inversely proportional to the creep rate, use the data to estimate the creep activation energy Q and the stress exponent n for this material. [8]

Temperature (°C)	Creep rupture life (hours)				
	σ =196 MPa	σ =177 MPa	σ = 157 MPa	σ = 137 MPa	σ = 118 MPa
600	6,715	11,500	20,850	43,000	104,820
650	-	-	2,200	-	-
700	-	-	400	-	-

Table I

(c) Advise on the suitability of this material for pressurised pipe-work in a nuclear power plant operating at 700 °C with a maximum stress of 200 MPa. [5]

2 (a) A steel containing 0.6 wt% C and an aluminum alloy with 4 wt% Cu were held at temperatures of $\sim 0.85T_m$ (T_m is the melting temperature) for 45 minutes and then quenched into water. For each of the alloys, sketch the microstructures before and after quenching and identify the phases present. Explain how the quenched microstructures arise. Comment on the yield stress and toughness values of these alloys in the quenched condition. Note: The M_f temperature for a steel containing 0.6 wt% C is approximately -30 °C. [6]

(b) For both alloys, explain how a further heat treatment might be used to improve the properties. In each case, use annotated sketches to show how the microstructure changes during heat treatment. [7]

(c) For the aluminum alloy with 4 wt% Cu, sketch and briefly explain the variation in room temperature yield stress with time during heat treatment. Explain why there is a peak in yield stress. [7]

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3 (a) Explain why dashpots and linear elastic springs are useful for describing the viscoelastic behaviour of polymers. Write down the governing equations for each element. Without carrying out any calculations, sketch the strain versus time for the case of an imposed step in stress when a spring is connected with a dashpot in series and in parallel. Explain why the plots take the forms you sketched. [6]

(b) The deformation response of a polymer can be represented by a dashpot of viscosity η in series with a spring of elastic constant k_1, as shown in Fig. 1(a).

(i) Derive the governing differential equation relating the stress to the strain, and hence find the harmonic response. [6]

(ii) The complex modulus $\bar{E}$ of this particular spring/dashpot model can be written in the form

$$\bar{E} = \frac{k_1\omega^2\tau^2 + ik_1\omega\tau}{1+\omega^2\tau^2}$$

where τ $(=\eta\ k_1^{-1})$ is the relaxation time and ω is the angular frequency. Plot on log-log scales the imaginary component of the complex modulus as a function of $\omega\tau$ over the range $0.01 < \omega\tau < 100$. Estimate the glass transition temperature of the polymer at a frequency of 1 Hz assuming that the spring constant is $k_1 = 10^7$ N m^{-2} and the viscosity η is given by

$$\eta = \frac{6\times10^8}{T}\text{ Pa s}$$

where T is the absolute temperature. [4]

(c) The above model (b) is loaded in parallel with a spring of elastic constant k_2, as shown in Fig. 1(b). Use the "electrical circuit method" to write down the harmonic response. [4]

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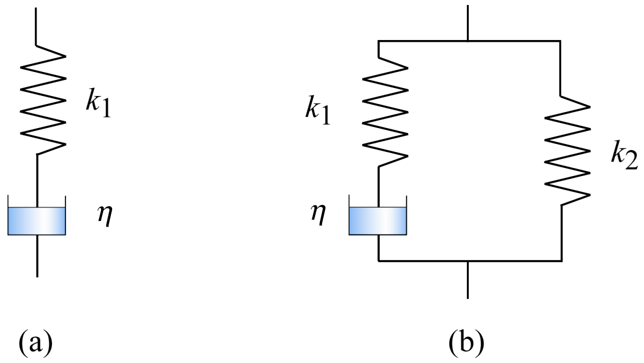

Fig. 1

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SECTION B

4 (a) Explain carefully what is meant by a eutectic reaction and a peritectic reaction in the phase diagram of a binary alloy. Use diagrams to define the following features of the phase diagram of a binary alloy: (i) eutectic point; (ii) eutectoid point; (iii) hypereutectic region; (iv) hypoeutectic region. Give examples of the feature in each case by reference to a specific phase diagram. [6]

(b) Explain carefully how the lever rule is used to determine phase proportions in a two-phase region, $\alpha + \beta$, in the phase diagram of a binary alloy. Derive equations for the mass fractions, W_α and W_β, at a given constitution point in a binary alloy in terms of the overall composition of the alloy and the compositions of the two phases involved. [6]

(c) Identify the phases present at a constitution point of 40 wt% Sn, 60 wt% Pb and 150 °C for a lead-tin binary alloy using the phase diagram in the Materials Data Book. Determine the compositions of these phases and calculate the relative amount of each phase present in terms of its mass fraction. What assumptions are required to convert mass fraction into volume fraction, and why would knowledge of the volume fraction be useful? [5]

(d) Prior to 2006, a binary alloy of composition of 60 wt% Sn and 40 wt% Pb was important for practical applications. Identify this application and state briefly why this particular alloy worked well. State why this binary alloy is no longer used for this purpose. [3]

5 (a) Explain why polymers are used widely in manufactured products. [4]

(b) Explain why thermoplastics, thermosets and elastomers exhibit different mechanical properties. Why are thermoplastics well suited to the manufacture of products? [4]

(c) Describe carefully how crystallinity determines the physical properties of a thermoplastic and how this is controlled during processing. [5]

(d) Identify the process used to manufacture a polyethylene terephthalate (PET) fizzy drinks bottle. Describe carefully the steps in this process and explain how it influences the strength of the final product. Why is it desirable to limit the degree of crystallinity in this process to around 20%, and how is this achieved in the process itself? [4]

(e) Give two reasons why perspex (PMMA) and high-density polyethylene (HDPE) are used for aircraft windows and water pipes, respectively. [3]

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6 (a) Explain carefully heterogeneous and homogeneous nucleation in liquids, giving examples to support your answer. Describe the factors that determine the rate at which a liquid transforms homogeneously to a solid, using graphs of the key variables to illustrate your answer, where appropriate. [8]

(b) Show that the critical radius r^* for the stable, homogeneous growth of a spherical nucleus of a solid phase in a liquid is given by

$$r^* = \frac{2\gamma T_E}{\left|\Delta H_V\right| \Delta T}$$

where $\left|\Delta H_V\right|$ is the magnitude of the enthalpy change on solidification per unit volume, γ is the interfacial surface energy per unit area, T_E is the temperature at which the transformation takes place and ΔT is the undercooling ($= T_E - T$, where T is the temperature). [4]

(c) The critical radius for the homogeneous nucleation of ice in clean water contained in a beaker is approximately 1 nm. Given that the surface energy between ice and water is $0.025\ \text{J m}^{-2}$, the enthalpy change per unit mass of water on freezing is $335\ \text{kJ kg}^{-1}$ and the density of ice is $920\ \text{kg m}^{-3}$, determine the undercooling at which *homogeneous nucleation* of ice takes place in clean water. Assuming that the critical volume and equation for r^* are the same as those for homogeneous nucleation, estimate the undercooling required for *heterogeneous nucleation* on the beaker walls if the angle of contact, θ, between the ice and the beaker is typically 10°, as illustrated in Fig. 2. You may assume that the volume of a spherical cap, V, is given by

$$V = \frac{2\pi r^3}{3}\left(1 - \frac{3}{2}\cos\theta + \frac{1}{2}\cos^3\theta\right)$$

where r is the radius of the sphere.

Comment on the difference between the degree of undercooling required for heterogeneous and homogeneous nucleation of ice in clean water. [6]

(d) Describe briefly one example of how controlled nucleation is used to determine material properties in a practical fabrication process. [2]

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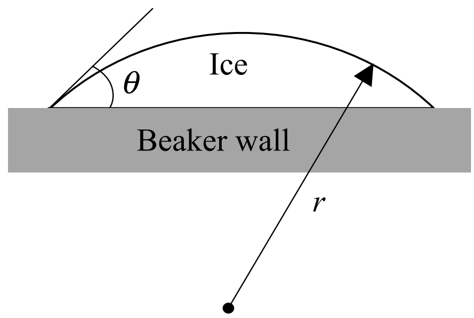

Fig. 2

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