Version JHD/7 with answers

EGT1
ENGINEERING TRIPOS PART IB

Tuesday 31 May 2016   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 (a) Give a brief description of the following processes and explain the origin of the thermodynamic driving force involved:

(i) recrystallization in cold worked aluminium; [3]

(ii) flow of water across a semi permeable membrane separating pure water from water containing a solute where both are initially at the same hydrostatic pressure; [3]

(iii) change in size of $CuAl_2$ precipitates in over-aged Al-Cu alloy; [3]

(iv) quenching of medium carbon steel into cold water from a temperature above 800 °C. [3]

(b) The properties of a single 1D polymer chain of monomer length a can be modelled using the random walk model in which each element adds a vector length either to the left or the right of the previous element. The Gibbs free energy, G, of a system is related to its internal energy, U, temperature, T, pressure, p, volume, V and entropy S by the following relation $G = U + pV - TS$. The entropy of a system is given by $S = k \ln \Omega$ where k is Boltzman's constant and Ω is the number of possible configurations.

(i) Explain qualitatively why, from thermodynamic considerations, a single polymer chain can behave like a spring when stretched. [5]

(ii) Explain qualitatively the relationship between the stiffness of the polymer chain and temperature. [5]

(iii) Give two reasons why in a real, as opposed to an ideal, single polymer chain the random walk model is an oversimplification. [3]

2 (a) An uncoated sample of aluminium and an uncoated sample of mild steel are exposed to damp air. The aluminium sample is observed to be not significantly affected by corrosion while visible rust becomes rapidly apparent on the mild steel sample.

(i) Explain why corrosion is a more significant problem in mild steel than in aluminium. [3]

(ii) Describe three models of corrosion which relate sample mass to time during corrosion and sketch the behaviour. State which model applies to the corrosion of the aluminium and steel samples. [4]

(iii) Outline three methods for the prevention of corrosion in steel structures and explain the mechanism by which they function. [6]

(b) A sample of 304 grade stainless steel was left in air for 7 days after being freshly cut. After this time a surface layer 2 nm thick was observed to have formed. (304 grade stainless steel contains by weight 18 %Cr and 8 %Ni with the rest being Fe.)

(i) State the material of which you would expect the surface layer to be primarily composed. Why does this compound form? [2]

(ii) Immediately after the cutting of the sample the surface layer is observed to thicken linearly with time but after a few hours this relationship breaks down. Explain this observation and describe the layer growth limiting mechanism in both cases. [5]

(iii) Write down the expected relationship between the thickness of the surface layer and time after 7 days. Estimate the thickness of the surface layer after one year. [5]

3 (a) Figure 1 shows the Al-Cu phase diagram.

(i) Provide the proportion and compositions of the phases present at the points labelled A, B and C on the phase diagram. [7]

(ii) Sketch and label the microstructure expected for a sample cooled slowly to room temperature from each of A, B and C. [7]

(b) Two samples of the Al-Cu alloy of the composition shown at A in Fig. 1 were heated to 590 °C for a long period of time. One was cooled slowly to room temperature and the other cooled rapidly.

(i) Explain the origin of the difference in microstructure between the two different samples. [3]

(ii) If both samples were subsequently aged by being heated to ∼200 °C, sketch on the same graph how you would expect the hardness of the samples to change with time. Explain the origin of the major features of the behaviour. [8]

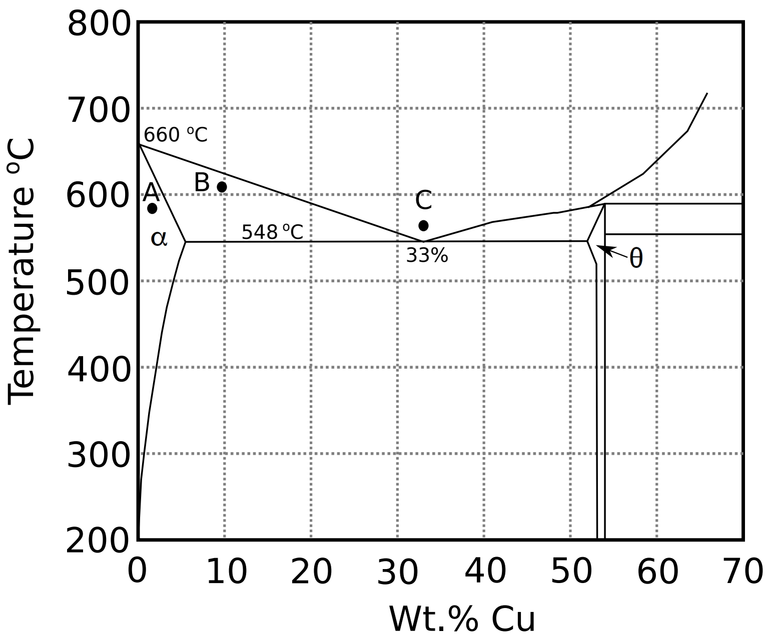

Fig. 1

SECTION B

4 The following statements about a range of material-process scenarios contain errors. Identify which parts of the statements are incorrect, explaining your reasoning, and in each case provide the correct interpretation.

(a) Segregation is the non-uniform distribution of solute in a casting, due to faster nucleation nearer the mould walls. [5]

(b) Quenching of non-heat-treatable Al alloys from high temperature leads directly to an equilibrium microstructure of average strength because recovery is avoided. [5]

(c) A carbon steel containing Ni and Cr failed catastrophically after welding because it lost its corrosion resistance. [4]

(d) An 80 mm diameter bar of low alloy steel and a 40 mm diameter bar of medium carbon steel were quenched from 850 °C into water at 20 °C, and tempered for one hour at 500 °C. The hardness at the centre of the low alloy steel was higher because the cooling rate was slower, allowing the formation of alloy carbides during the quench. [6]

(e) Stretch blow moulding of thermoplastics increases the strength because the thin cross-section promotes faster cooling and the formation of spherulites. This is not the case in fibre drawing. [5]

5 (a) Figure 2(a) shows the failure surfaces for a uniaxial fibre composite, with the fibres aligned in the 1-direction and Figure 2(b) shows the failure surface for a biaxial composite with equal numbers of fibres in the perpendicular 1- and 2-directions. With reference to the failure mechanisms of the composite, briefly explain the relative magnitudes of the failure strengths for uniaxial tensile and compressive loading in the 1- and 2-directions in each case. [6]

(b) A thin-walled cylindrical composite shaft of radius r and wall thickness t is produced by filament winding, with the ability to wind fibres helically at angles of $\pm 45^\circ$ to the axis of the shaft. The shaft is loaded in torsion by a torque T, and may be twisted in either direction.

(i) Use the Structures Databook to show that that the shear stress τ in the wall of the shaft is given approximately by [3]

$$\tau = \frac{T}{2\pi r^2 t}$$

(ii) Loading in pure shear with stress τ is equivalent to principal stresses of magnitude $\sigma_1 = \tau$ and $\sigma_2 = -\tau$ respectively. Sketch these two stress states in the appropriate orientations for twisting the shaft in each direction. Hence explain the choice of filament winding angle. [5]

(iii) A prototype tube of radius $r = 40$ mm and thickness $t = 4$ mm is manufactured with fibres wound in one direction only, effectively giving a uniaxial composite with respect to the principal stresses. Use the failure surface in Fig. 2(a) to find approximate values of σ_1 and σ_2 at failure, for twisting in both directions. Hence find the failure torques for both directions of twist. [5]

(iv) A second prototype of the same dimensions is wound with equal numbers of fibres in the +45 $^\circ$ and the -45° directions, giving a balanced layup. Use the failure surface in Fig. 2(b) to find the failure torque for both directions of twist. [4]

(v) The shaft may also be subjected to bending loads. What modification to the arrangement of fibres in the tube wall would be advisable? Explain your reasoning. [2]

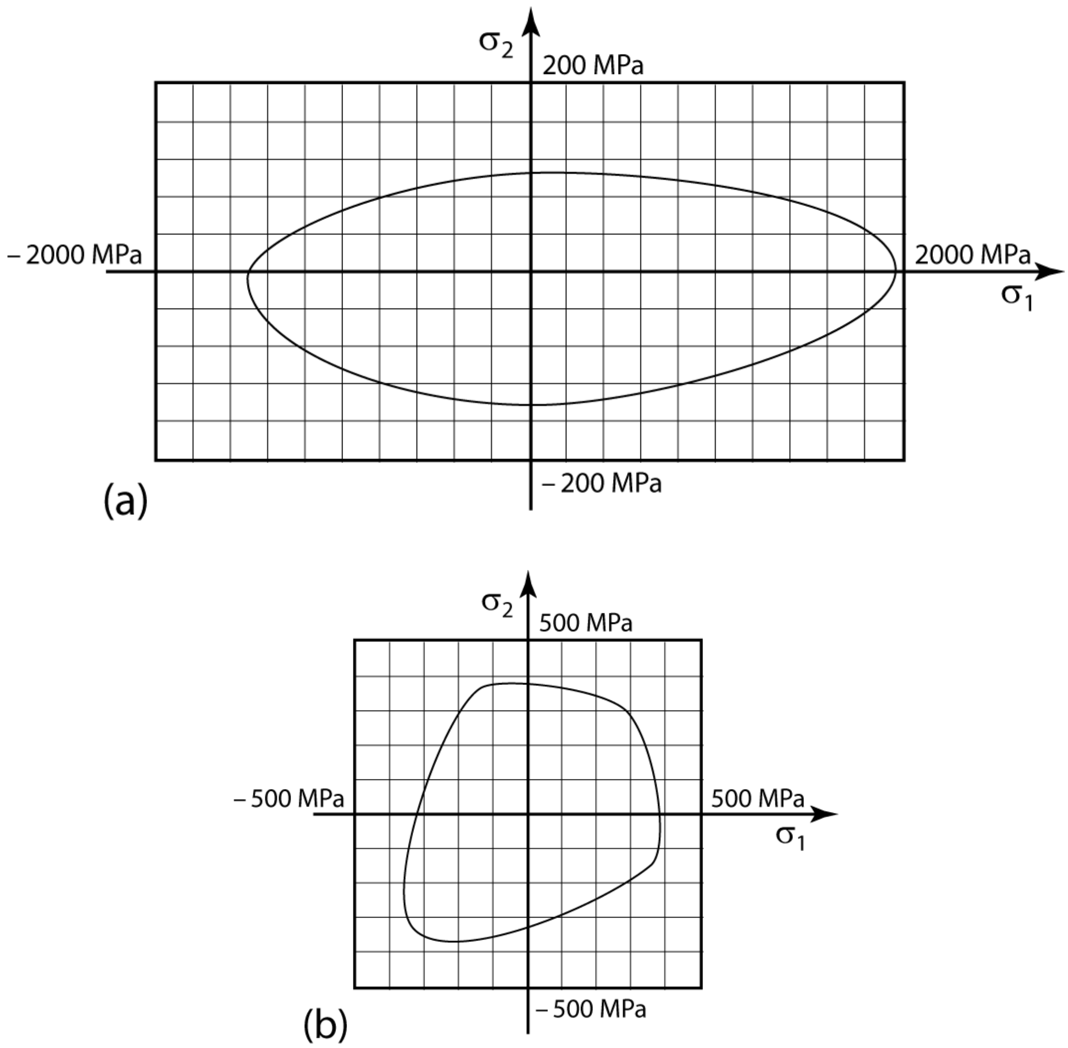
σ2
200 MPa
– 2000 MPa
2000 MPa
σ1
– 200 MPa
(a)
σ2
500 MPa
– 500 MPa
500 MPa
σ1
– 500 MPa
(b)

Fig. 2

6 Figure 3 shows the plane strain forging between parallel rigid platens of a long bar of width $2w$ and height $2h$. The out-of-plane dimension is much larger than $2w$. A constant sticking friction stress τ equal to the shear yield stress k acts on the interfaces between the bar and the platens. The vertical and horizontal components of stress at a distance, x, from the centre line are given by $p(x)$ and $\sigma(x)$ respectively.

(a) By considering the horizontal equilibrium of one half of the forging, show that the horizontal stress at $x = 0$ is given by $\sigma_{\text{max}} = kw/h$. [4]

(b) Using the Tresca yield criterion, find the maximum and minimum pressure acting between the platen and the bar, identifying clearly where these occur, and stating any assumptions. [7]

(c) Find an expression for the average pressure acting between the platen and the bar, in terms of the uniaxial yield stress Y, w and h. You may assume that the variation in pressure is linear between the maximum and minimum values. [4]

(d) The metal case of a mobile phone is 1 mm thick with planar dimensions 60 mm $\times$ 120 mm. Use the result in part (c) to estimate the average pressure needed to hot forge this case in a material of yield stress 50 MPa, assuming sticking friction conditions. Hence explain why components such as this are not forged. Give three reasons why it would be preferable to make the case from cold rolled sheet. [7]

(e) Kitchen foil is made by cold rolling commercial purity aluminium. Explain the benefits of lubricating the rollers, and of passing two sheets through the roll gap simultaneously. [3]

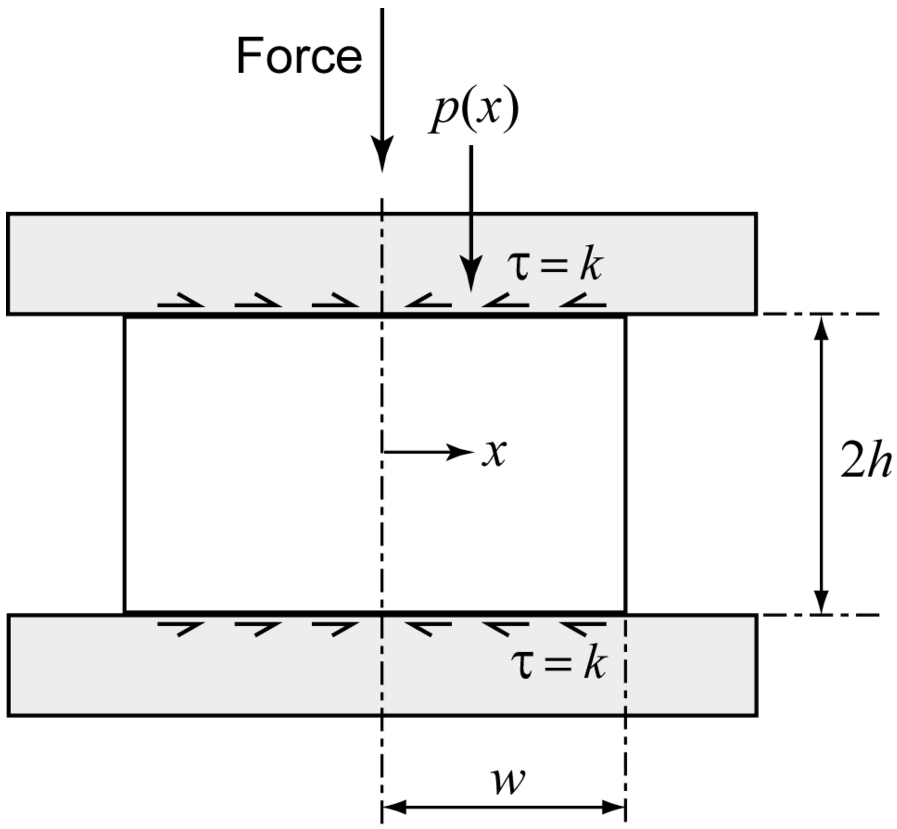

Fig. 3

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Numerical Answers

Q3 (b,iii) $\approx$ 14nm

Q5 (b,iii) 4.2 and 5.8 kNm

Q5 (b,iv) 9.2 kNm

Q6 (b) $p_{max} = k(2+w/h)$, $p_{min} = 2k$

Q6 (c) $p_{average} = (p_{max} + p_{min})/2) = k(2+w/2h) = Y(1+w/4h)$

Q6 (d) 800 MPa