ENGINEERING TRIPOS PART IB

Monday 5 June 2000 9 to 11

Paper 3

MATERIALS

*Answer not more than **four** questions.*

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.*

(TURN OVER

1 (a) Define what is meant by *hardenability* and *critical cooling rate* in the heat treatment of steels. [4]

(b) In the Jominy end-quench test, a steel specimen is austenitised in a furnace, transferred to a rig and quenched on one end using a jet of water. The magnitude of the cooling rate at a temperature of 500°C is well approximated by the equation

$$\frac{\partial T}{\partial t} = \frac{1.75\times10^{-3}}{x^2} \ \mathrm{K\,s^{-1}}$$

where x is the distance from the quenched end of the Jominy specimen (in metres). Explain why the cooling rate of interest is defined at a temperature of 500°C. [2]

Long cylindrical bars of steel quenched in oil have a cooling rate at their centre which decreases with increasing bar diameter. Figure 1 shows the linear correlation between the diameter of oil-quenched bar, and the distance along the Jominy specimen, which have the same cooling rate. Find an equation relating Jominy distance to bar diameter quenched in oil. Derive a second equation relating cooling rate to bar diameter quenched in oil, and plot a graph showing this relationship. [5]

(c) A camshaft of diameter 25 mm is to be made from Ni-Cr-Mo low alloy steel. A heat treatment is required to produce 100% martensite through the entire cross-section. The critical cooling rate (CCR) for a range of these steels may be found empirically from the equation

$$\log_{10}(\mathrm{CCR\ in\ K\,s^{-1}}) = 4.3 - 3.27\,\mathrm{C} - \frac{(\mathrm{Mn + Cr + Mo + Ni})}{1.6}$$

where the symbol given for each element denotes its weight percentage. Using your graph from part (b) and the data in Table 1, select the optimum steel for the camshaft. [6]

Explain why a bulk and a surface heat treatment are subsequently conducted on the camshaft. [3]

	Weight percentages					Cost
Steel	C	Mn	Cr	Mo	Ni	£/kg
A	0.30	0.80	0.50	0.20	0.55	0.65
B	0.36	0.80	1.50	0.25	1.50	1.25
C	0.41	0.80	0.50	0.25	0.55	0.70
D	0.40	0.80	0.65	0.55	2.55	0.80

Table 1

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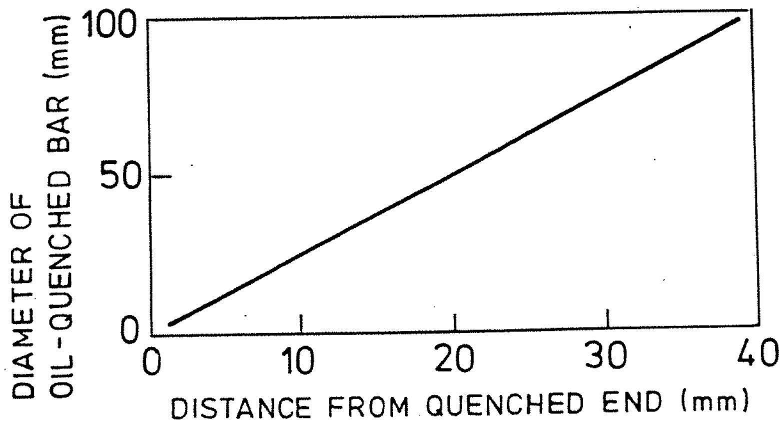

Fig. 1

2 (a) What are the principal design-limiting properties of polymers, and what are their advantages over other classes of materials? [6]

(b) Thermoplastics may be classified as amorphous or semi-crystalline. Explain these terms, and give an example of a difference in the properties of these two classes. Give one example of a thermoplastic from each class, with a typical application of each. Briefly describe one molecular factor and one processing factor which control the degree of crystallinity in a semi-crystalline thermoplastic. [8]

(c) A small plastic bucket is to be manufactured by injection moulding or rotational moulding. The designer wishes to estimate the manufacturing cost for various batch sizes, using the cost equation

$$\text{Cost per part } C = C_m + \frac{C_L}{\dot{n}} + \frac{C_C}{n}$$

where C_m is the cost of the material used per part, $\dot{n}$ is the production rate, and n is the batch size. Define the meaning of the terms C_L and C_C.

Using the data in Table 2, determine the cheapest process for batch sizes of 1,000 and 50,000. Why might the amount of material used (and therefore the material cost) differ for the two processes? [6]

	C_m (£)	C_L (£/hr)	$\dot{n}$ (parts/hr)	C_C (£)
Injection moulding	0.25	20	120	5000
Rotational moulding	0.20	20	40	1000

Table 2

(TURN OVER

3 (a) In the selection of materials in design, explain (with examples) the meaning of the terms *objective*, *constraint* and *merit index.* [6]

(b) A simple heat exchanger between two liquids at different temperatures is constructed from a thin-walled tube, as shown in Fig. 2. The heat conducted per unit area of tube surface is given by

$$q = \lambda \frac{\Delta T}{t}$$

where λ is the thermal conductivity of the tube material, ΔT is the (constant) temperature difference between the liquids, and t is the wall thickness. The tube is a thin-walled metal cylinder of fixed length and radius, but the wall thickness may be varied. It must support a specified pressure difference Δp between the liquids, without failing. The designer wishes to maximise the heat flow per unit area of tube surface.

(i) Show that the required merit index for the heat exchanger tube is $M = \lambda \sigma_y$, where σ_y is the yield stress. [5]

(ii) Explain how to define a line for a constant value of M on the selection chart in Fig. 3, and hence use the chart to identify the best two classes of alloy for the heat exchanger tubes. [5]

A separate copy of Fig. 3 is provided, and should be handed in with your answer.

(iii) Comment on two other material property requirements which should be considered for this design problem. [2]

(iv) For one of your selected materials, discuss what problems might occur if the tubes are joined to the surrounding container by welding. [2]

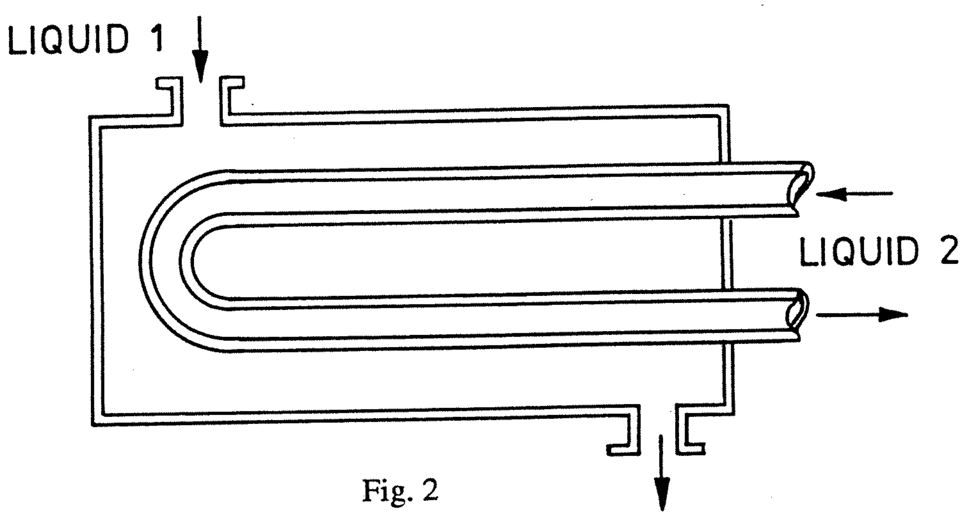

Fig. 2

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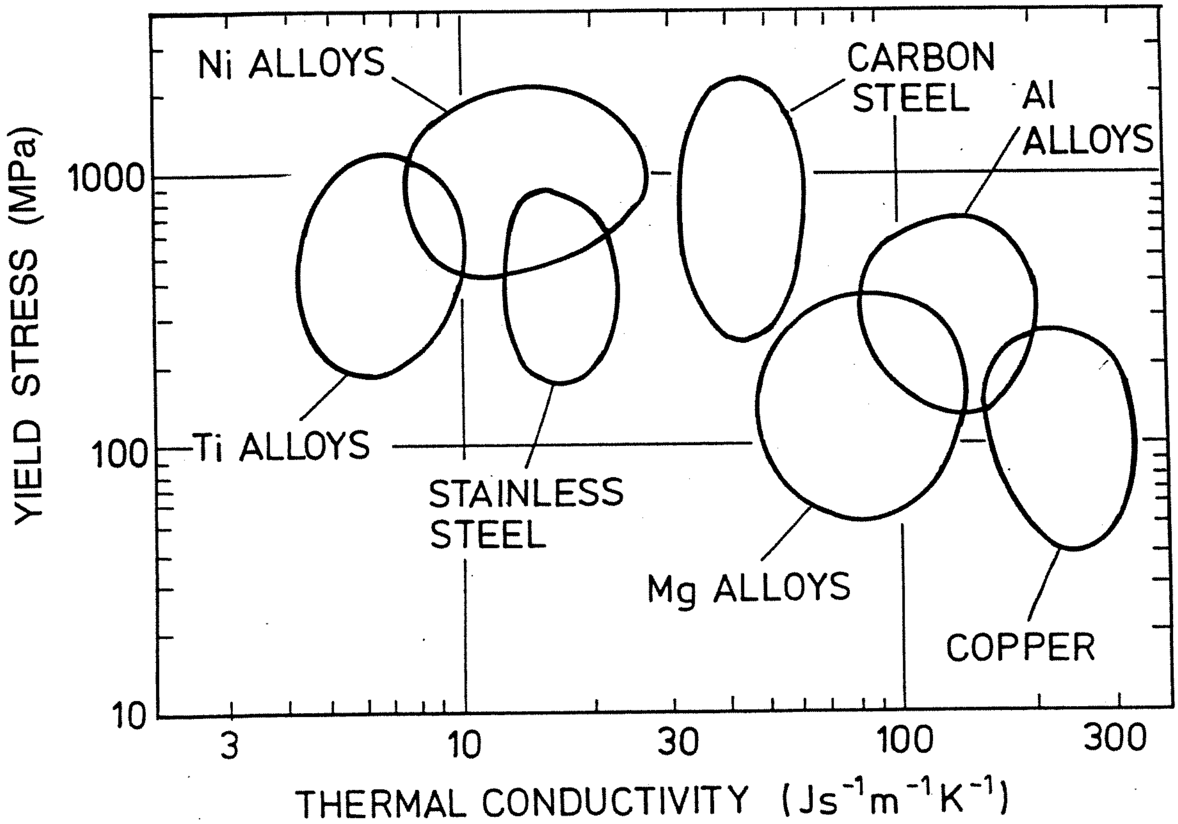

Fig. 3

4 (a) Explain carefully the mechanisms of *work hardening*, *recovery* and *recrystallisation*. How are these processes used to control the grain size of wrought alloys, and what factors influence the final grain size? [8]

(b) Describe with sketches the two ways in which dislocations interact with precipitates in heat-treatable aluminium alloys. Explain how the transition between these two mechanisms of precipitation hardening controls the shape of the ageing curve for these alloys. [7]

(c) Discuss briefly two of the factors which are driving the development of lower weight cars. How are aluminium alloys currently used to reduce vehicle weight, and how might they be used more extensively in future? [5]

5 (a) Explain briefly why the strength of ceramics is controlled by a 'weakest link' theory. [3]

(b) The probability of survival P_S of a ceramic specimen of volume V_0 carrying a uniform tensile stress σ is given by

$$P_S(V_0) = \exp\left\{-\left[\frac{\sigma}{\sigma_0}\right]^m\right\}.$$

Define the parameters σ_0 and m. [2]

Use this equation to show that, for a volume V of the same material, weakest link theory dictates that

$$P_S(V) = \exp\left\{-\frac{V}{V_0}\left[\frac{\sigma}{\sigma_0}\right]^m\right\}. \quad [4]$$

Derive a relationship for the ratio of the failure stresses in uniform tension, for volumes V_1 and V_2, for a constant probability of survival. [4]

(c) Tensile tests were conducted on specimens of SiC of length 20 mm and diameter 5mm. For an applied stress of 270 MPa the probability of survival was 50%, and the value of m was found to be 8.

Figure 4 shows a matrix crack in a ceramic fibre composite which is bridged by unbroken SiC fibres, of diameter 25 µm. An estimate of the stress which one fibre in the composite can carry can be made by considering just the volume of a fibre which is exposed between the faces of the crack. Calculate the stress which one fibre can carry with a survival probability of 50%. What assumption must be made about the SiC used for the tensile tests and for the fibres? Comment on the toughening potential of SiC fibres for brittle matrix composites. [7]

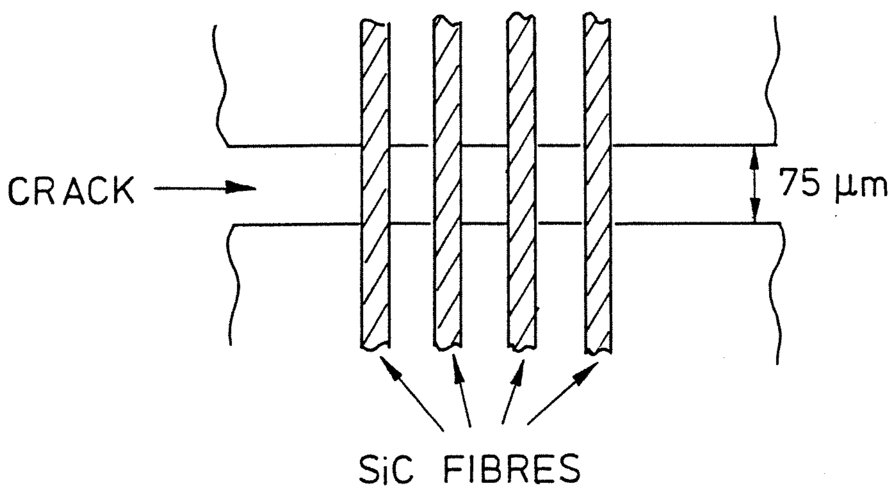

Fig. 4

6 (a) Define what is meant by a *eutectic reaction*. Explain briefly why solders are usually alloys of eutectic composition. [4]

(b) Figure 5 shows the phase diagram for the tin-lead system.

A tin-lead alloy containing an atomic fraction of lead $X_{Pb} = 60$ at.% is cooled slowly from the melt. For temperatures of 190°C and 175°C:

(i) Identify the phases present and calculate the proportions of the phases (*by weight*).

(ii) Sketch the microstructures expected, distinguishing clearly between single phase and two-phase regions.

Calculate the proportions of the phases (*by weight*) within any two-phase regions of the microstructures.
What further microstructural change may occur with cooling from 175°C to room temperature? [12]

(c) Describe briefly what is meant by segregation, and explain why segregation may be a problem in metals processing. [4]

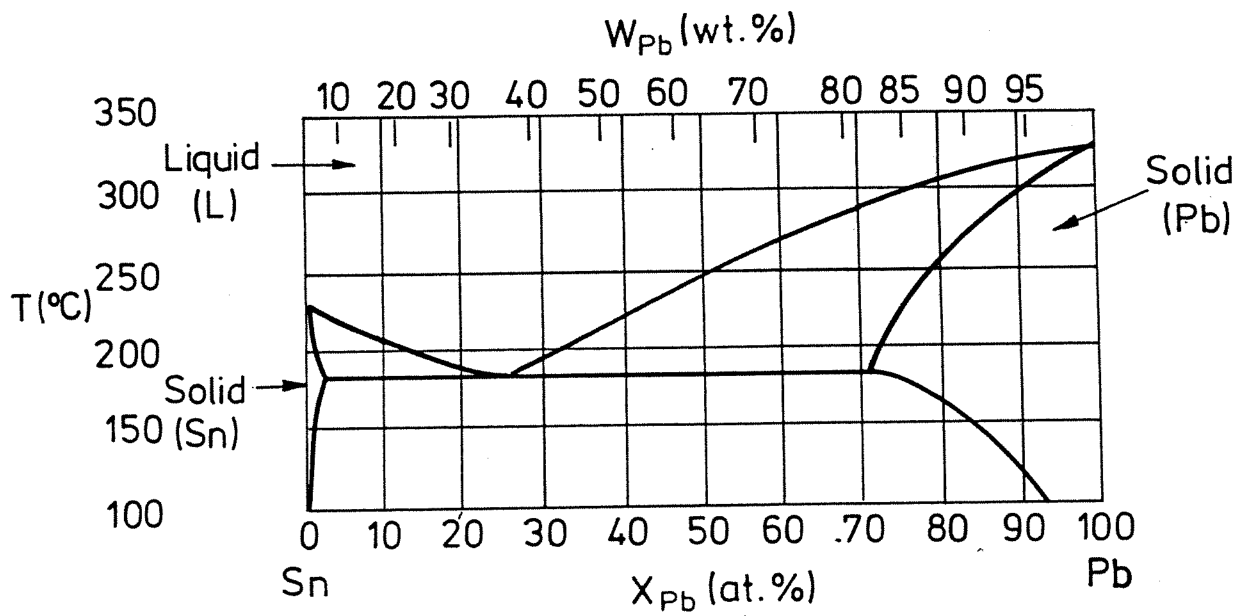

Fig. 5

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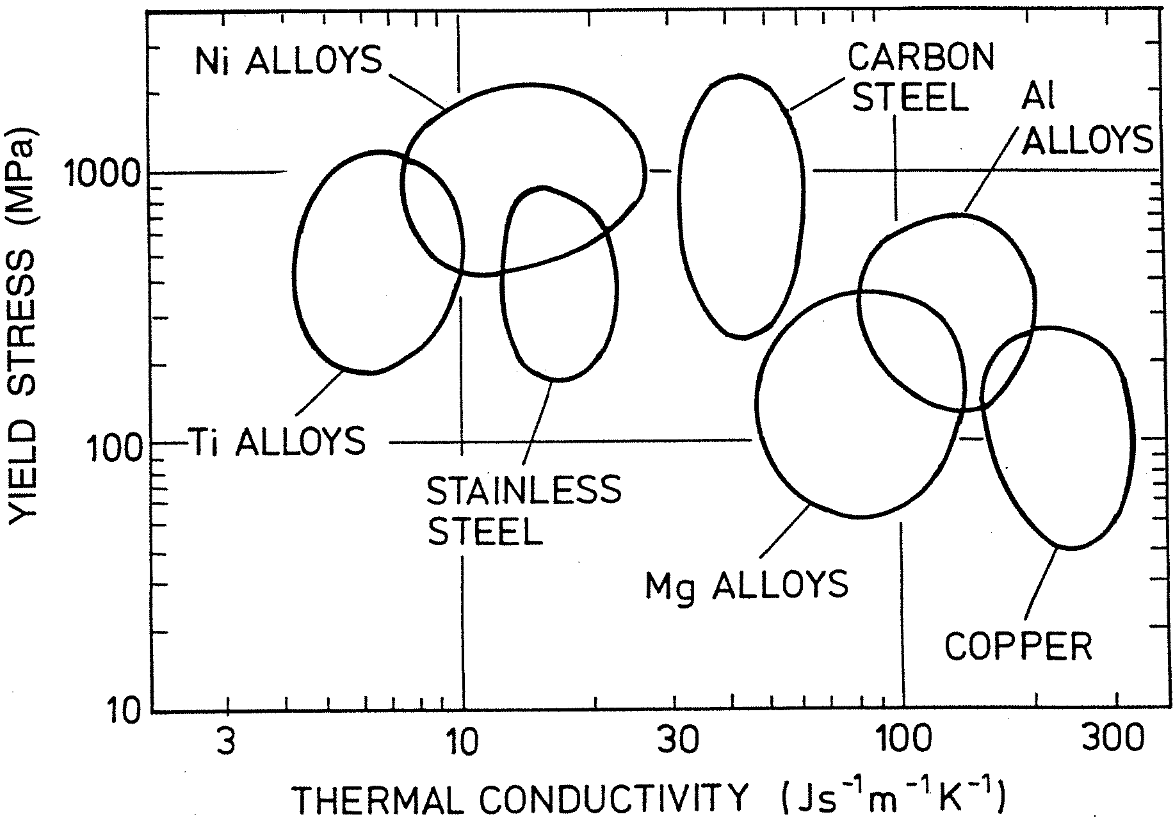

Fig. 3