ENGINEERING TRIPOS PART IB

Tuesday 4 June 1996 9 to 11

Paper 3

MATERIALS

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

(TURN OVER

1 (a) Explain briefly what is meant by the following terms:

(i) a eutectic reaction;

(ii) a eutectoid reaction.

(b) Fig. 1 shows the phase diagram for the copper-antimony system. The phase diagram contains the intermetallic compound marked "X" on the diagram. Determine the chemical formula for this compound.

(c) The copper-antimony phase diagram contains *two* eutectic reactions and *one* eutectoid reaction. For *each* reaction:

(i) identify the phases involved;

(ii) give the compositions of the phases;

(iii) give the temperature of the reaction.

(d) An alloy containing 95 weight% antimony is allowed to cool from 650°C to room temperature. Describe the different phase changes which take place as the alloy is cooled and make labelled schematic sketches of the microstructure to illustrate your answer.

(e) Sketch a graph of temperature against time for the 95 weight% antimony alloy over the range 650°C to 500°C and account for the shape of your plot.

(cont.

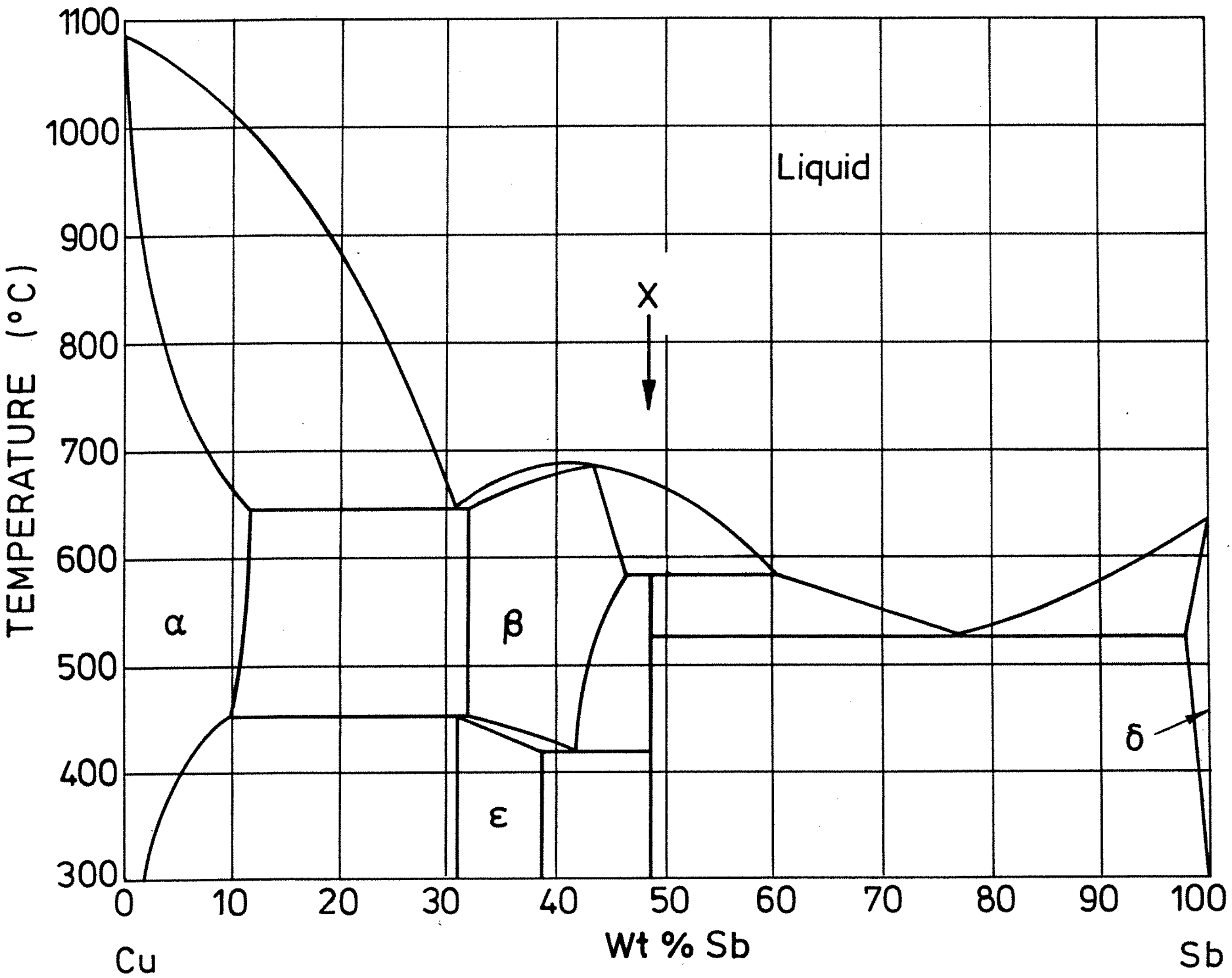

Fig. 1

(TURN OVER

2 (a) Describe briefly how the tensile strength of ceramic materials is determined by their microstructure. How may the tensile strength of ceramics be improved? Why are ceramics much weaker in tension than in compression?

(b) Figure 2 shows a cross-section through the wall of a tank for storing liquified natural gas (LNG) at atmospheric pressure. The outer skin of the tank is made from steel plate. The inner surface of the steel is coated with a continuous layer of brittle polyurethane foam 200 mm thick, which provides the required thermal insulation. The foam is glued securely to the steel at an assembly temperature of 10°C and is initially stress-free. During service in a temperate climate the steel remains at 10°C and the temperature of the LNG is –160°C.

Because of the thermal stress the brittle foam cracks through its thickness, compromising the integrity of the tank. Find the volume of the foam layer which gives a 50% probability of failure, and hence estimate the distance between adjacent through-thickness cracks.

You may assume the Weibull equation

$$P_S(V) = \exp\left\{-\frac{1}{V_0}\int_V \left(\frac{\sigma}{\sigma_0}\right)^m \mathrm{d}V\right\},$$

where $P_S(V)$ is the survival probability of a volume V of foam and m is the Weibull modulus. The thermal stress σ in the foam is given by

$$\sigma = \frac{\alpha \Delta T E}{(1-\upsilon)},$$

where α is the coefficient of thermal expansion, ΔT is a temperature difference, E is Young's modulus and υ is Poisson's ratio.

(cont.

Tensile tests were performed on foam specimens measuring $25 \times 25 \times 100$ mm. It was found that 50% of the specimens broke at or below a stress of 1.4 MPa. Other data for the foam are as follows:

$m = 8$;
$\alpha = 10^{-4}\ {}^{\circ}\mathrm{C}^{-1}$;
$E = 40$ MPa;
$\upsilon = 0.3$.

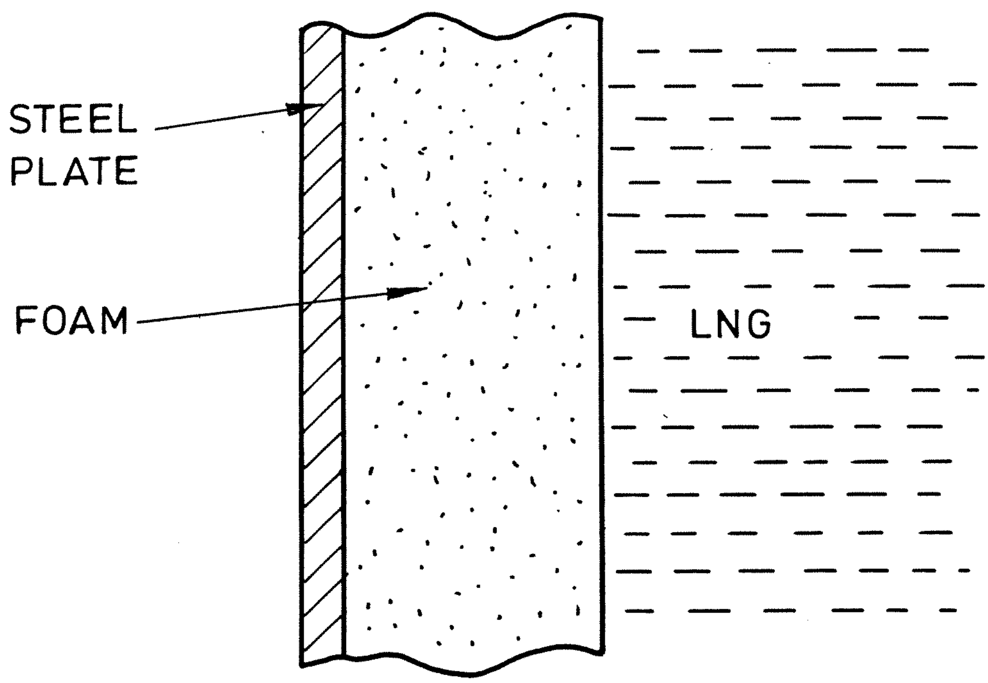

Fig. 2

(TURN OVER

3 (a) Samples of coarse-grained plain-carbon steel of eutectoid composition are to be heat-treated to produce the following metallurgical structures:

(i) pearlite;

(ii) bainite;

(iii) martensite;

(iv) tempered martensite.

In each case describe the structure (using simple sketches to illustrate your answer), and indicate a suitable heat treatment. You should make use of diagrams in the Materials Data Book as appropriate.

(b) A steering shaft made from a ferritic steel is to be case-hardened. The shaft is first case-carburised in a carbon-depositing atmosphere at 1000°C. The carbon-rich surface layer is then transformed to martensite by quenching. The diffusion of carbon into the steel is described by the equation

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

where C is the concentration of carbon at a distance x below the surface after time t, C_s is the concentration of carbon in the steel at the surface and C_0 is the initial carbon concentration in the steel. The diffusion coefficient D for carbon in steel at 1000°C is 6.68×10^{-11} m^2 s^{-1}. A graph of the error function erf(y) is given in Fig. 3. In the present situation $C_s = 1.20$ weight% and $C_0 = 0.15$ weight%.

The specification for the shaft requires the case to have a minimum Vickers hardness (Hv) in the as-quenched condition of 800 kgf mm^{-2} to a depth of 1.0 mm below the surface.

(cont.

Calculate the time for which the shaft must be carburised to reach the specification. What will be the Vickers hardness at the surface of the shaft after quenching?

[You will need to refer to Fig. 5.2 in the Materials Data Book.]

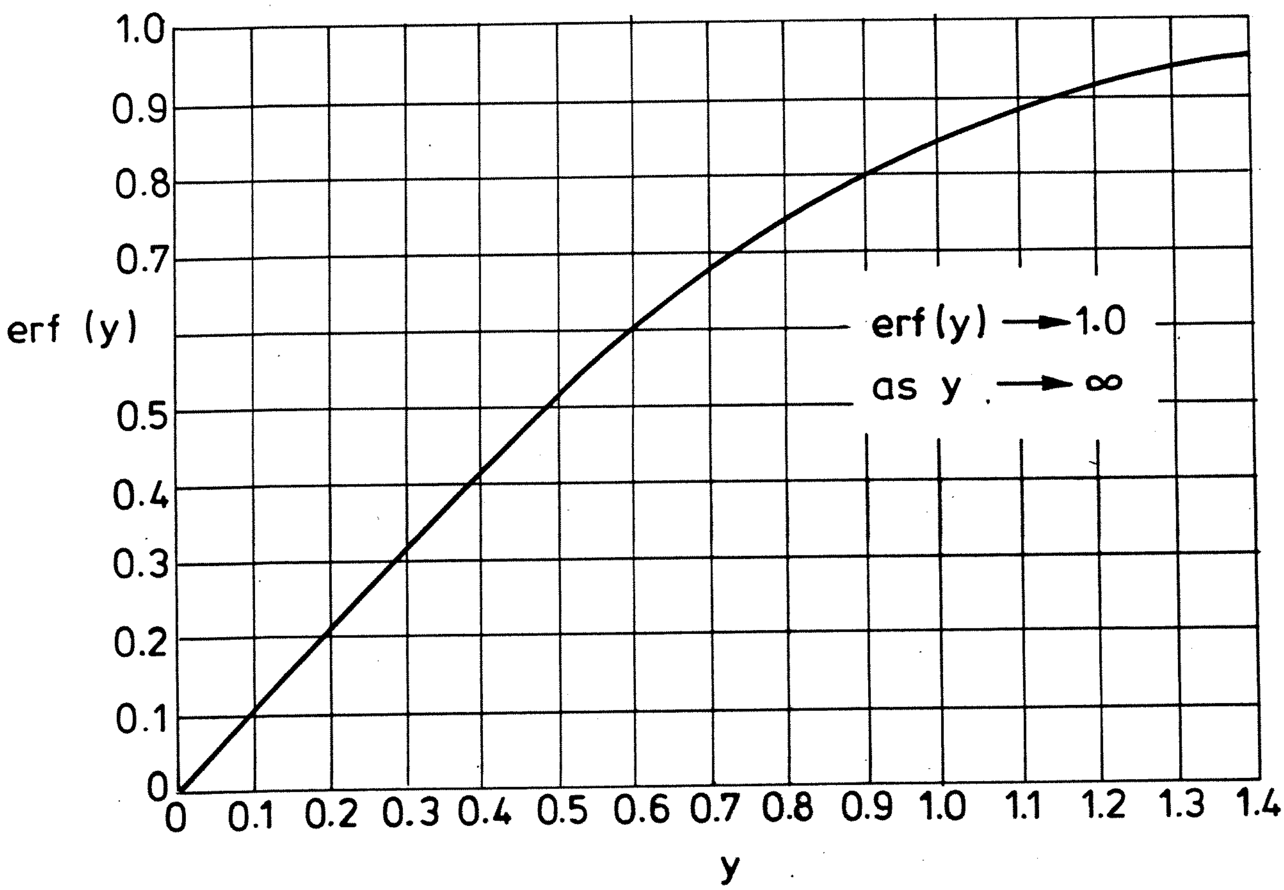

Fig. 3

4 (a) You have been asked to prepare an outline design for the pressure hull of a deep-sea submersible vehicle capable of descending to the bottom of the Mariana Trench in the Pacific Ocean. The external pressure at this depth is approximately 100 MPa, and the design pressure is to be taken as 200 MPa. The pressure hull is to have the form of a thin-walled sphere with a specified radius r of 1 m and a uniform thickness t. The sphere can fail in one of two ways:

external-pressure buckling, at a pressure p_b given by

$$p_b = 0.3E\left(\frac{t}{r}\right)^2,$$

where E is Young's modulus;

yield or brittle compressive failure at a pressure p_f given by

$$p_f = 2\sigma_f\left(\frac{t}{r}\right),$$

where σ_f is the yield stress or the compressive failure stress as appropriate.

The basic design requirement is that the pressure hull shall have the minimum possible mass compatible with surviving the design pressure.

(i) Derive an appropriate merit index to meet the design requirement for each of the two failure mechanisms.

(ii) Select the optimum material for the pressure hull from the materials listed in the table on the opposite page.

(iii) Determine the limiting failure mechanism for each material.

(cont.

[Hint: for each material calculate the mass and the wall thickness for both failure mechanisms.]

(b) Briefly describe the processing route which you would specify for manufacturing the pressure hull from each of the materials listed in the table, and comment on any particular problems which might be encountered. [You may assume that the detailed design will call for a number of apertures in the wall of the pressure hull.]

Material	E (GPa)	σ_f (MPa)	Density, ρ (kg m^{-3})
Alumina	390	5000	3900
Glass	70	2000	2600
Alloy steel	210	2000	7800
Titanium alloy	120	1200	4700
Aluminium alloy	70	500	2700

(TURN OVER

5 Explain the following observations.

(a) A bar of cold-drawn copper had a yield strength of 250 MPa. The bar was subsequently annealed at 600°C for 5 minutes. The yield strength of the annealed bar was 50 MPa.

(b) A sample of Al - 4 weight% Cu was cooled slowly from 550°C to room temperature. The yield strength of the slowly cooled sample was 130 MPa. A second sample of the alloy was quenched into cold water from 550°C and was then aged at 150°C for 100 hours. The yield strength of the quenched-and-aged sample was 450 MPa.

(c) The Young's modulus of natural rubber decreases from 3 GPa at –200°C to 3 MPa at room temperature whereas the Young's modulus of epoxy resin is approximately 10 GPa at both temperatures.

6 Discuss the problems involved in replacing more of the metal parts of a motor car with components made from polymers or polymer-based composites. Illustrate your answer by specific reference to the engine, gearbox, drive shafts, suspension and wheels.

END OF PAPER