ENGINEERING TRIPOS PART IB

Tuesday 5 June 2001 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.*

The answers to questions in each section should be tied together and handed in separately.

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SECTION A

1 (a) A gear wheel made from a plain carbon steel containing 0.2 wt% carbon is to be case-hardened. It is placed in a carbon-depositing atmosphere at 1000°C, and is then quenched to transform the surface to martensite. 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 parameter D_0 for carbon in steel is 9.1×10^{-6} m^{2}s^{-1}; the activation energy Q is 125 kJ mol^{-1}. A graph of the error function erf(y) is given in Fig. 1.

The wheel after quenching is required to have a carbon concentration of 0.45 wt% at a depth of 1.5 mm below the surface. Calculate the time for which the wheel must be carburised. [6]

(b) Two of the gear wheels in the as-carburised state are examined metallurgically at a depth of 1.5 mm below the surface. One of the wheels was quenched and one was cooled in air. The TTT diagram for plain carbon steel containing 0.45 wt% carbon is given in Fig. 2.

(i) Describe the structures you would expect to see in the two specimens, using simple sketches to illustrate your answer. [5]

(ii) Sketch stress-strain curves which you would expect to obtain for tensile tests on material with the same structures as these two samples, explaining the differences you identify. [7]

(iii) A third carburised gear-wheel is furnace cooled. Explain carefully the differences you would expect between this and the air-cooled sample in microstructure and mechanical properties at a depth of 1.5 mm below the surface. [2]

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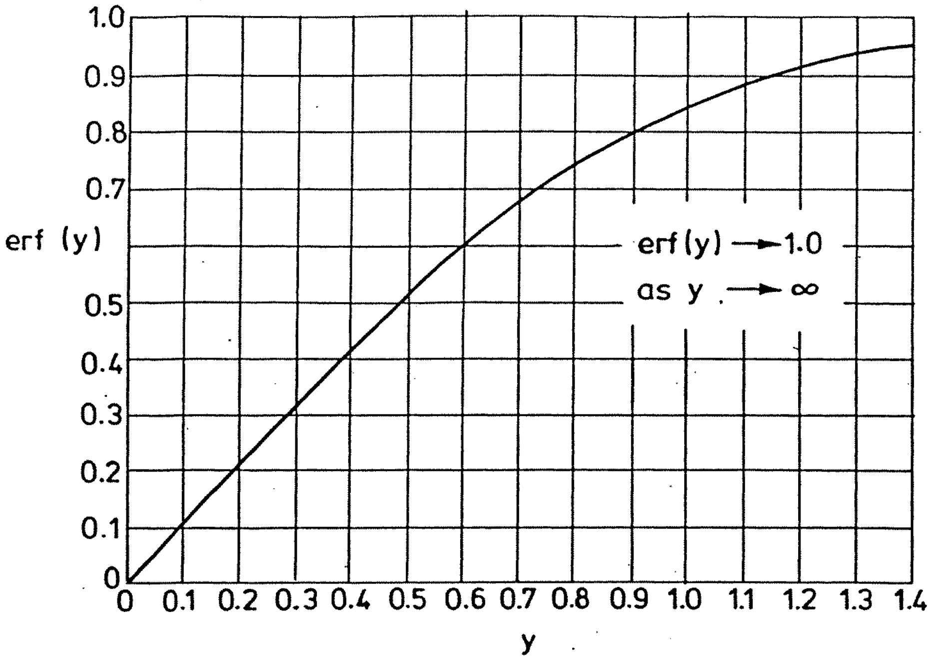

Fig. 1

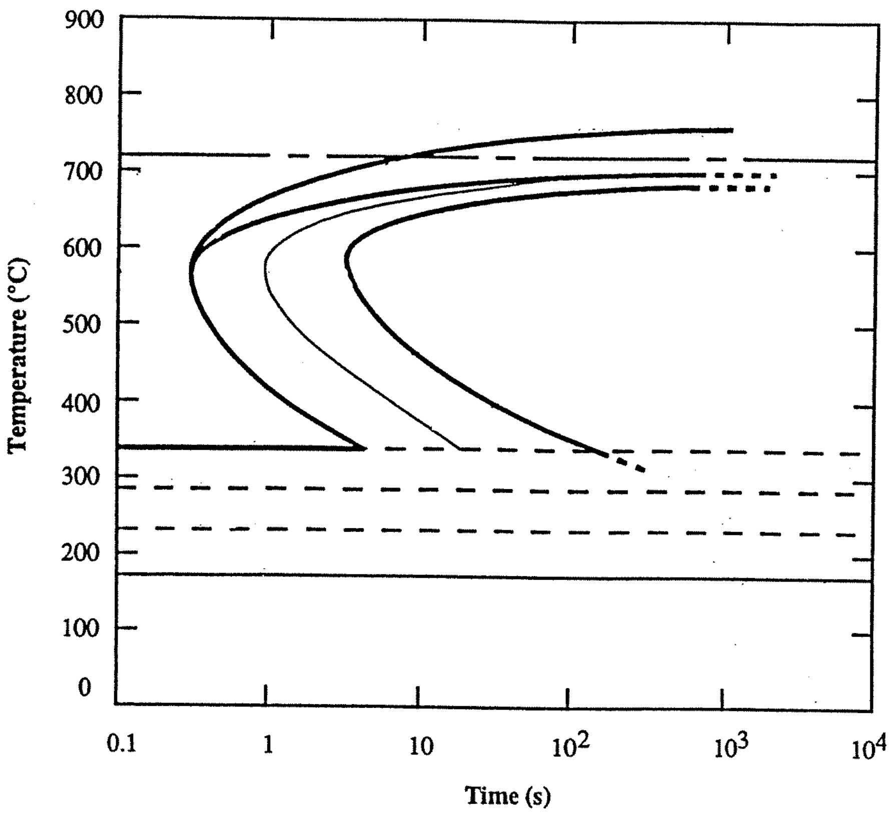

Fig. 2

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2 (a) The following alloys are cooled from the liquid state to the temperatures given, with the cooling rate being slow enough that equilibrium is maintained. In each case, make annotated sketches of the microstructures you would expect to see and give full descriptions of them (proportions of phases and chemical compositions). Refer to the equilibrium diagrams indicated in the Materials Data Book.

(i) Pb – 15 wt% Sn at 100°C (Fig. 4.2 in Data Book);

(ii) Pb – 50 wt% Sn at 180°C (Fig. 4.2 in Data Book);

(iii) Cu – 80 wt% Zn at 610°C and 500°C (Fig. 4.5 in Data Book). [15]

(b) For the alloys in parts (i) and (iii) of section (a), explain carefully what differences you would expect to find if the cooling rate were increased over the temperature range between the liquid state and the lowest temperature given. [5]

3 (a) Pieces from a strip of 2000 series aluminium alloy are to be heat-treated to obtain maximum hardness. Describe in outline the heat treatments you would use, and explain the microstructural changes which take place. [10]

How would you heat-treat this alloy to obtain maximum ductility? Explain your reasoning. [2]

(b) A strip of material with a specified grain-size is to be produced from 3000 series aluminium alloy by cold-rolling followed by annealing. Describe an experiment you could perform to determine the appropriate amount of rolling deformation and the annealing time. Explain what microstructural changes are taking place in the material at different stages in your experimental sequence. [6]

Why is grain size of importance in an alloy of this type? [2]

SECTION B

4 (a) Explain how the strength of ceramics is related to their microstructure (grain size and porosity). How is the microstructure determined by the manufacturing process? Describe in outline how articles can be made from ceramic. [8]

(b) A fairground side-show consists of ten bottles on a wall. Players throw balls to tip the bottles off the wall, and win a prize if all ten bottles smash. The bottles are made of material of density ρ, and can be modelled as hollow cylindrical tubes of height h, internal radius r and wall thickness $t = r/15$. The stress they suffer on hitting the ground is proportional to their weight. The probability of survival P_s of a sample volume V under stress σ is given by the equation

$$P_s = \exp\left\{-\frac{V}{V_0}\left[\frac{\sigma}{\sigma_0}\right]^m\right\}$$

where the constant m has the value 10.

In a first attempt to design the side-show, it is found that on average only one of the ten bottles smashes when it falls. Economic operation of the show requires that on average nine of the ten bottles will smash when they fall.

(i) To increase the probability of the bottles smashing, the dimensions h, r and t are to be increased by a constant factor until the required failure rate is reached. Determine the factor by which the dimensions of the cylinders must be scaled up to reach the required failure levels. [6]

(ii) The manufacturer cannot supply bottles of the required dimensions in time, and so an alternative method is needed to reach the required failure levels for the opening of the show. It is decided to increase the weight of the bottles by part-filling them with water to a depth αh. Water has density $\rho/3$. Determine the value of α. [6]

5 A flywheel is to be used for a regenerative braking system in town buses. The most efficient flywheel will store as much energy per unit weight as possible. Performance is limited by the maximum stress in the flywheel not exceeding the failure stress of the material. The flywheel is a solid disc of material density ρ, with fixed radius R and thickness t, rotating with angular velocity ω, which can vary.

The energy stored in the flywheel is

$$U = \frac{\pi}{4} \rho R^4 t \omega^2$$

and the maximum stress in the flywheel is given by

$$\sigma_{max} = k \rho R^2 \omega^2$$

where k is a constant.

(a) Derive a merit index for the best material for the flywheel. [6]

(b) From the strength-density chart in Fig. 3, rank the following materials in decreasing order of suitability according to your merit index: Al_2O_3; GFRP; High Strength Steel; Lead Alloys; Tungsten Alloys. Would you expect the value of strength for Al_2O_3 on the chart to be correct for this application? [5]

(c) The flywheel is to be mass-produced at minimum cost. Choose the one material from the list in (b) which you consider would be most suitable for the flywheel, justifying your choice and explaining why other materials from this list with apparently more favourable merit indices might be less suitable. [6]

(d) Briefly describe how the flywheel could be manufactured using your chosen material. [3]

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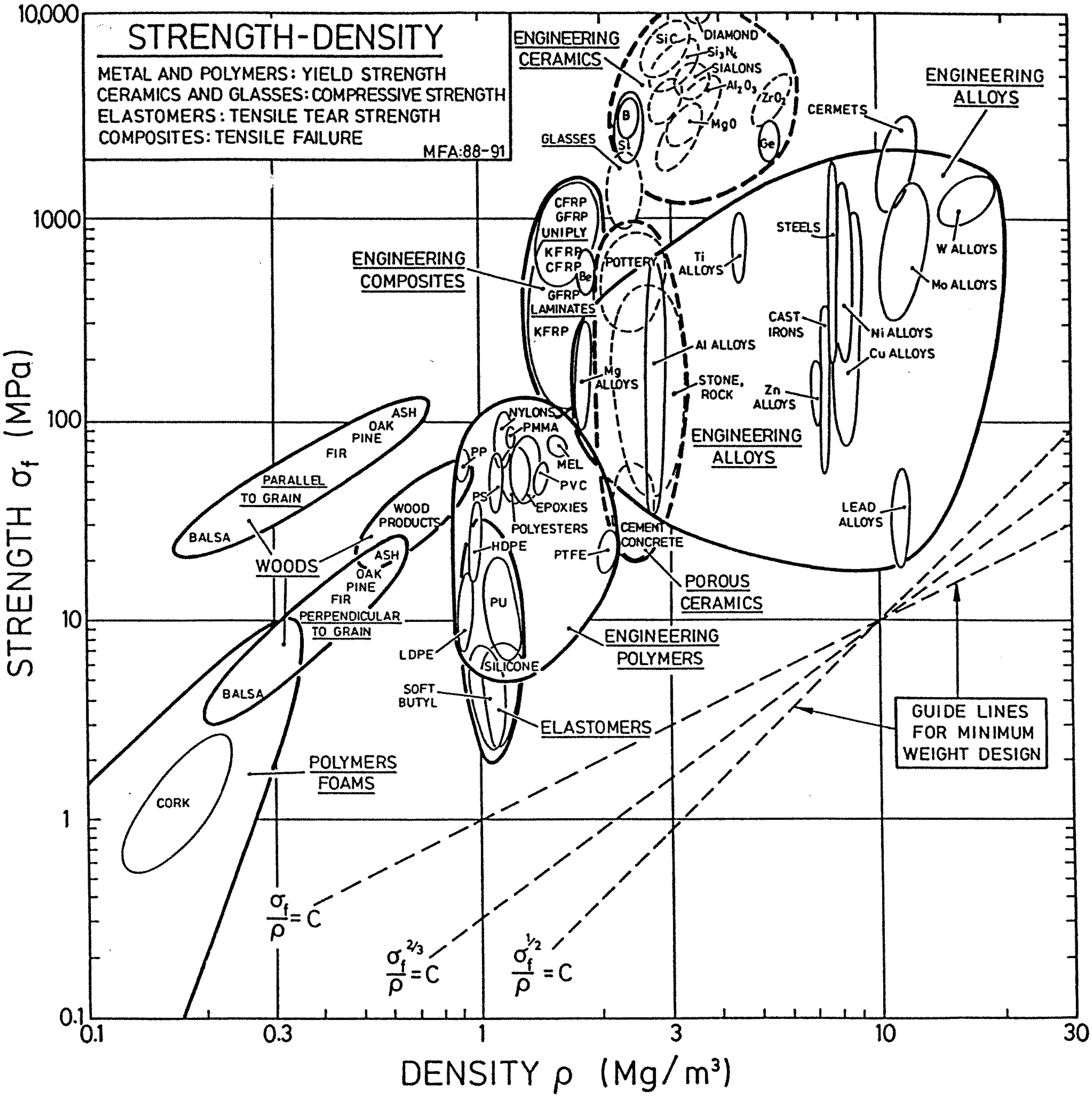

Figure 3

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6 (a) Underground water pipes made from HDPE have to be put under stress to bend them to shape when they are laid around curves. After a few years, they retain this shape when removed from the ground. Explain this observation in terms of the molecular structure of the polymer. [5]

(b) The following articles are to be manufactured from polymer. In each case, explain what properties are required and justify your choice of polymer. The following polymers are available: PC, PMMA, Nylon, HDPE.

(i) The lenses of safety goggles. [4]

(ii) A sealing ring for the lid of a glass container which can be used between room temperature and 50°C for keeping the contents either moist or dry. [4]

(c) Three identical specimens of polypropylene are deformed in tension. Two are deformed at room temperature, one at a low strain-rate and the other at a very high strain-rate; the third specimen is deformed at a low strain-rate at a temperature of −196°C. Sketch stress-strain curves for the three specimens, explaining the differences between them. [7]

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