ENGINEERING TRIPOS PART IB

Tuesday 3 June 1997 9 to 11

Paper 3

MATERIALS

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

The **approximate** *number of marks allocated to each part of a question is indicated in the right margin.*

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1 (a) The hardness and high melting point of structural ceramics make them difficult to shape into engineering artefacts. Discuss briefly how these and other characteristics of a structural ceramic affect the ways it can be manufactured into an engineering component. [5]

(b) Explain why we observe such large variability of measured tensile strength within a batch of manufactured ceramic components. How does this influence the design methodology for this class of engineering material? [5]

(c) Under constant applied tensile stress, σ, a flaw of size a in a tensile specimen of fused silica can undergo stable growth that leads to delayed fracture. The crack growth rate, da/dt, is dependent on the crack tip stress intensity factor K and can be described by an empirical power law of the general form:

$$\frac{da}{dt} = AK^n$$

where A and n are constants. It may be assumed that $K = \sigma\sqrt{\pi a}$. Failure occurs when K is equal to the fracture toughness K_c .

In the proof testing of fused-silica windows for Skylab, the proof-test stress ratio R is defined as σ_p/σ_a, where σ_p is the proof stress which is greater than the applied or working stress, σ_a . Find an expression for the maximum possible crack length a_p in the window which just survives the proof stress, σ_p, and an expression for the crack length at failure a_c at the working stress, σ_a. Hence show that the minimum time to failure, t_f, of a window is approximately given by:

$$t_f = \frac{2{K_c}^{2-n}\left(R^{n-2}\right)}{A(n-2)\pi\sigma_a^2} \ .$$

You may assume that the value of n is much greater than 2. [5]

(Cont.

(d) Figure 1 shows a time-to-failure diagram with axes (log scales) of t_f and σ_a. Superimposed are a series of straight lines of failure-probability, P_f, for Skylab's windows as a function of applied stress, σ_a, obtained from independent tests on the windows.

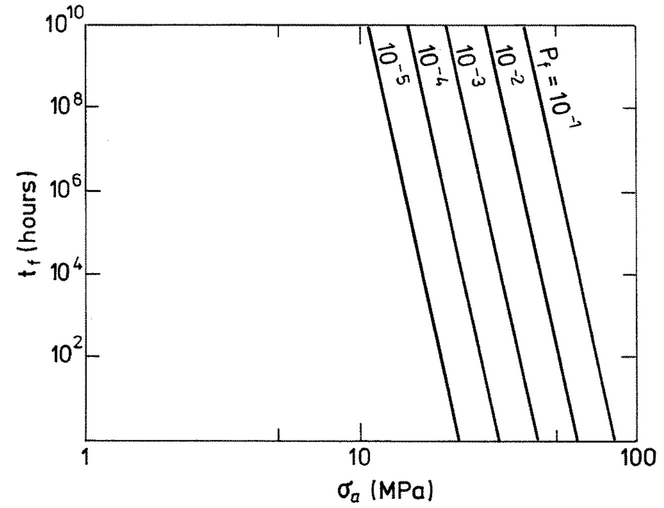

Fig. 1 Time-to-failure diagram for silica windows

(i) Construct on the diagram the line of predicted minimum time-to-failure versus operating stress for fused-silica windows which have undergone a proof test with $R = 2.5$. For fused silica, $K_c = 0.7\ \mathrm{MPa}\sqrt{\mathrm{m}}$, $n = 20$ and $A = 0.725$.

A separate diagram is provided for this purpose which should be handed in as part of your answer.

Skylab's windows are designed to withstand a maximum applied stress, σ_a, of 50 MPa without fracturing. If a proof test stress ratio $R = 2.5$ is used, what is the guaranteed life-time? From a batch of windows, roughly how many (as a %) would actually fail this proof test? [3]

(ii) If future Skylabs have to be designed for longer life-times and, as a result, the windows have to be guaranteed to last for 50 years whilst at the same time allowing for only 1 window in a 1000 to fail the proof test, how could this be accomplished? [2]

2 (a) Explain why the yield strength of heavily cold-worked pure aluminium strip falls with time when it is subsequently annealed at 550 °C, whereas an alloy of aluminium-4% copper (by weight) becomes harder with time after quenching in water from 550 °C and re-heating to 150 °C. [12]

(b) (i) The aluminium alloy skin of the Concorde aircraft is deliberately "under-aged". What is meant by this term? Why is this important for its successful long-term performance? [5]

(ii) A batch of aluminium alloy-rivets for an aircraft wing were inadvertently "over-aged". What steps can be taken in order to salvage this batch of rivets? [3]

3 (a) What variations in the architecture of the molecules of thermosetting and thermoplastic polymers make for a clear distinction between these two classes of engineering plastics? Discuss briefly how the structural differences between them account for the large contrasts in their yield strength and ductility. [6]

(b) Make a sketch that illustrates the temperature dependence of Young's modulus of a semi-crystalline polymer and a highly-cross-linked epoxy resin. Indicate in your sketch the temperatures at which there is a significant change of state within each polymer. Identify the range of temperature over which the semi-crystalline polymer can be moulded successfully. [4]

(c) In the processing of a part made of a semi-crystalline polymer, what are the likely effects of cooling-rate on the microstructural features of the moulding? [4]

(d) Identify **one** polymer in each of the following classes, giving a typical engineering application for each one: **amorphous thermoplastic, semi-crystalline thermoplastic, thermosetting resin**. Explain briefly why the particular polymer is suitable in the application chosen. [6]

4 Figure 2 shows the stresses acting at any instant on an element of a plate compressed by forging under plane-strain conditions between parallel overhanging platens. The thickness of the plate is $2h$ and its width is $2w$ which is much greater than $2h$. The depth of the plate into the page is very much greater than $2w$. The distribution of pressure is $p(x)$; the horizontal stress σ_X is uniform through the thickness of the plate and may be assumed a principal stress; and the magnitude of the shear stress τ between plate and platen is *assumed to be constant throughout* and is given by $|\tau| = m\,\sigma_Y/2$ where σ_Y is the yield stress and m is a constant less than unity. The total forging load is F per unit depth of plate.

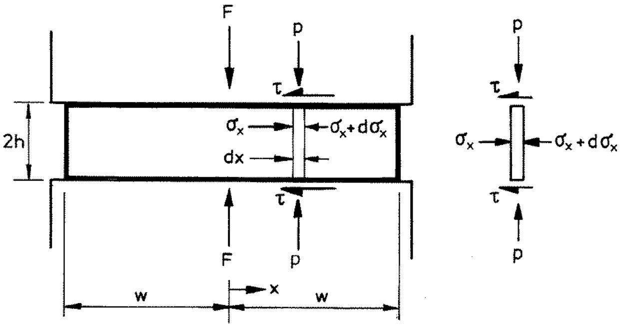

Fig. 2 Element of the work piece during the forging process

(a) (i) Derive a differential equation of equilibrium for the variation of σ_X with x in terms of τ. [8]

(ii) Hence, show that the pressure increases inwards from $p = \sigma_Y$ at both edges of the plate to a maximum according to the expression:

$$p = \sigma_Y\left[1+\frac{m}{2}\left(\frac{w-|x|}{h}\right)\right]$$

Sketch the pressure distribution $p(x)$ on the plate. [3]

(b) What will be the total force F per unit depth if $w = 6h$ and $m = 0.1$? [3]

(c) Explain how the force F is affected by:

(i) the yield strength of the metal; [2]

(ii) increasing shear stress between work piece and platen; [2]

(iii) the reduction in thickness as the operation proceeds. [2]

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5 (a) Explain why the change in lattice structure of iron from face-centred cubic to body-centred cubic is an essential transformation process in the manufacture of steel components. [3]

(b) Define the term "hardenability of steel" and explain briefly ways in which the hardenability of a plain carbon steel can be increased. What are the disadvantages of using a steel of high hardenability in welded structures? [4]

(c) The Time-Temperature-Transformation diagram of an alloy steel is shown in Fig. 3. A thin strip of this steel of length 200 mm is placed into a pre-heated laboratory heat-treatment furnace and quickly comes up to a uniform temperature of 915 °C.

By gripping the end of the strip nearest the front of the furnace and carefully withdrawing half of its length beneath a partially open door, the end now exposed to the outside air cools rapidly. Within only 5 seconds, there exists a stable linear temperature gradient from the cold end at 15 °C to the portion of strip within the furnace. The 100 mm of strip still in the furnace remains at 915 °C.

After 2 hours, the steel strip is withdrawn quickly and quenched into water.

(i) Describe the microstructure of the steel strip after the 2 hours immediately before the water quench at the following locations measured from the cold end: **30 mm; 40 mm; 50 mm; 70 mm; 75 mm; 90 mm; 100 mm**. What changes to these microstructures would result as a consequence of the water quench? [10]

(ii) If the steel strip is now reheated to 400 °C for 20 minutes, what changes in microstructure would you expect to observe? [3]

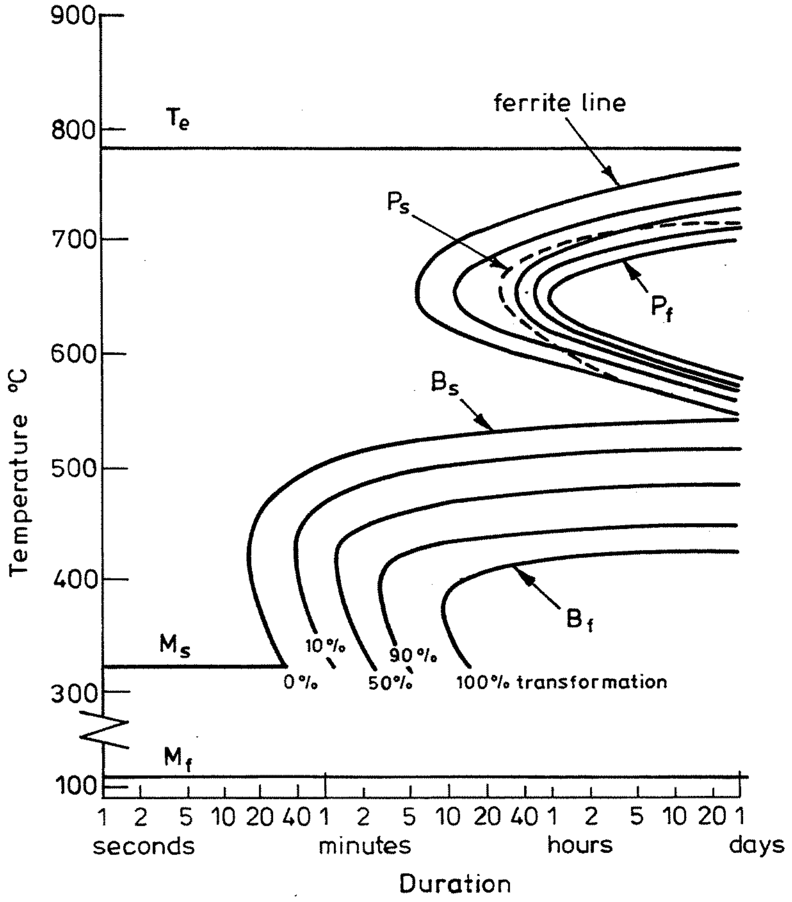

Fig. 3 TTT diagram for a low-alloy steel

6 The prime objective of the compressor of a turbofan engine is to increase the thrust of that engine by maximising the air flow. The large fan blades at the front of the engine perform this function operating over the temperature range -30 °C to 50 °C (Fig. 4).

Important design requirements are that the air-flow rate must be maximised; secondly, the blade must not fracture due to the centripetal forces; and finally, the blade's weight must be kept to a minimum.

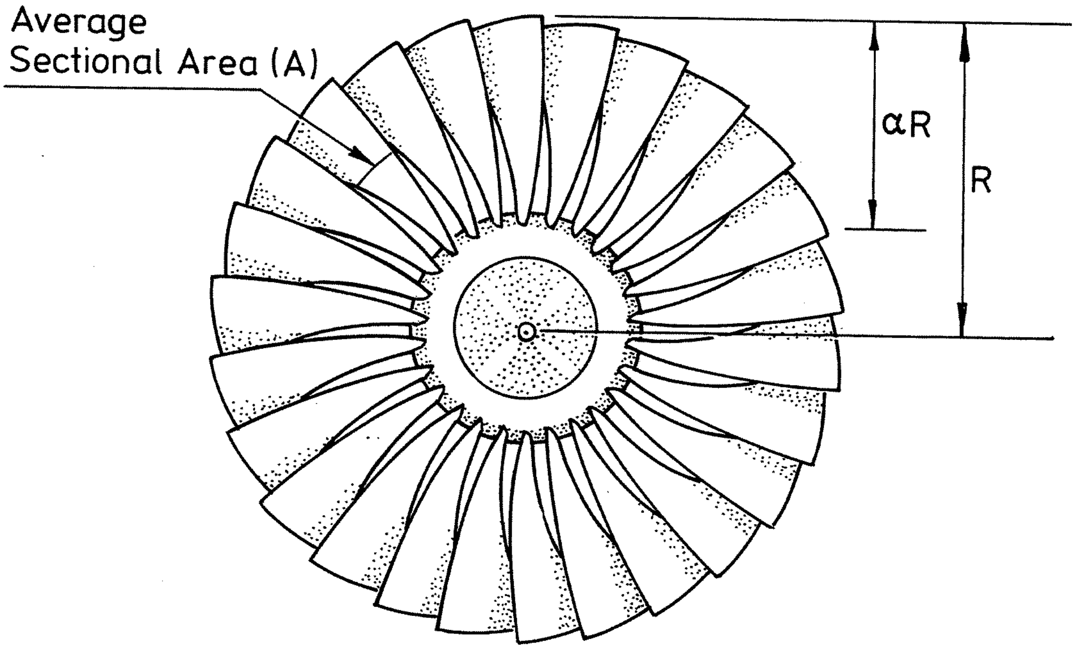

Fig. 4 Schematic of the compressor fan blades of a turbofan engine .

The geometrical features of the turbofan are defined in Fig. 4. The fan radius R is a constraint on the design and is therefore specified. An individual blade has length αR, where α is that fraction of the fan radius which is the actual blade (the remainder is part of the rotor assembly). The average sectional area of the blade, A, is also specified and can be assumed constant along the blade's length. The blade is to be made of a material of density ρ.

(Cont.

(a) Find a merit index M_1 which should be maximised in order to satisfy the requirement for minimum weight. [2]

(b) For a rotational speed ω, the stress at the root of the blade is given by:

$$\sigma = \frac{\rho\omega^2 R^2}{2}\alpha(2-\alpha).$$

The volume-flow rate (in m^3/s) of air is given by $Q = A\omega R^3$ where A is a fan constant. Derive an expression for the maximum flow rate Q which is compatible with the blade's fracture stress σ_f, including a factor of safety, S_f, into the equation.

Hence, define the merit index M_2 which should be optimised in order to meet the design requirement of maximising the flow rate Q without the blade fracturing. [6]

(c) Construct the guide-lines for both merit indices M_1 and M_2 on the Materials Selection Chart a copy of which is shown in Fig. 5 over the page. **A separate copy is provided which should be included as part of your answer.** [2]

(d) Make a short list of the most promising candidate materials from those displayed on the Materials Selection Chart. Discuss briefly any other critical issues that should be taken into account in making a material selection. [5]

(e) Propose a manufacturing route by which the blade could be fabricated from **one** chosen material. Make a short list of the principal factors which affected your choice of process method. [5]

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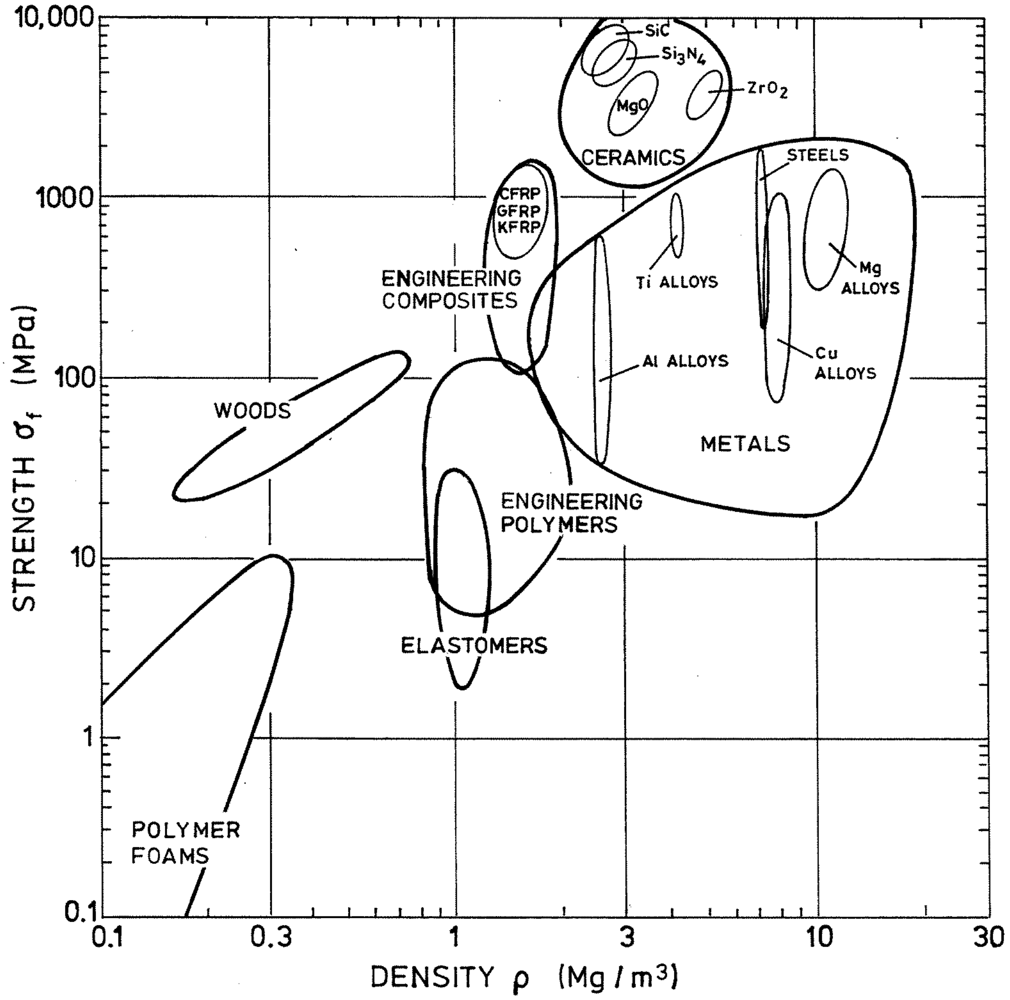

Fig. 5 A Materials Selection Chart of Strength vs Density

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