ENGINEERING TRIPOS PART IIA
MANUFACTURING ENGINEERING TRIPOS PART 1

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Wednesday 29 April 2009 9 to 10.30

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ENGINEERING TRIPOS PART IIA: Module 3C2
MANUFACTURING ENGINEERING TRIPOS PART I: Paper P4B

MATERIALS PROCESS MODELLING AND FAILURE ANALYSIS

*Answer not more than* ***three*** *questions.*

*All questions carry the same number of marks.*

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

*There are no attachments.*

STATIONERY REQUIREMENTS
Engineering Tripos:
Single-sided script paper

Manufacturing Engineering Tripos:
20 page answer booklet, rough work pad

SPECIAL REQUIREMENTS
Engineering Data Book
CUED approved calculator allowed

**You may not start to read the questions printed on the subsequent pages of this question paper until instructed that you may do so by the Invigilator**

Version: 3

1 (a) In the Jominy end-quench test, a steel bar with a uniform initial temperature $T_{\mathrm{i}}$ is water-cooled at one end to ambient temperature $T_0$ . State the assumptions which would be made in a simple analytical model for the temperature distribution in the bar as a function of time. [15 %]

(b) The analytical solution for the magnitude of the cooling rate in the end-quench test at a fixed intermediate reference temperature $T_{\mathrm{r}}$ (where $T_{\mathrm{i}} \geq T_{\mathrm{r}} \geq T_0$) and at a distance $x$ along the bar from the quenched end has the form

$$\frac{\partial T}{\partial t} = -\frac{C\,a}{x^n}$$

where $a$ is the thermal diffusivity of the bar, and $C$ is a constant (with units of temperature) that depends on $T_0$, $T_{\mathrm{r}}$ and $T_{\mathrm{i}}$ . Use a dimensional argument to find the value of the exponent $n$. [25 %]

(c) An equivalent finite element model for the end-quench test on a bar of length 125 mm makes the same thermal assumptions as for the analytical model. Explain why 1-D elements would be sufficient for this analysis.

Table 1 shows the cooling rate at a certain reference temperature predicted by the FE model for various distances from the quenched end. Explain why using two 1-D elements would not be sufficient to produce these results, and suggest changes to the FE mesh that would provide sufficient accuracy.

Sketch a graph to compare the cooling rate as a function of distance predicted by the finite element method with the form of the analytical solution. Estimate the range of $x$ over which the two solutions agree, and account for the discrepancy outside this range. [45 %]

(cont.

(d) In a Jominy end-quench test, the cooling rate at the reference temperature was measured to be 30 K $s^{-1}$ at a distance of 4 mm from the quenched end. Compare this with the values predicted by the models in part (c), and suggest a reason for any discrepancy. [15 %]

| $x$ (mm) | $-\partial T/\partial t$ (K $s^{-1}$) |
|---|---|
| 1 | 2455 |
| 2 | 614 |
| 5 | 100 |
| 10 | 33 |
| 20 | 14 |
| 50 | 7 |
| 100 | 4.5 |

Table 1

(TURN OVER

2 (a) An intense localised heat input is applied instantaneously at time $t = 0$ to the cross-sectional plane $x = 0$ in an infinitely long strip of constant cross-sectional area at uniform initial temperature $T_0$. The impulse solution for the distribution of temperature $T$ in the bar for $t > 0$ is:

$$T(x,t) - T_0 = C t^{-1/2} \exp(-x^2 / 4at)$$

where $C$ is a constant and $a$ is the thermal diffusivity of the strip material.

(i) Derive an expression for the peak temperature rise as a function of $x$. [25%]

(ii) In a processing trial, a long thin strip of steel at an ambient temperature of 20 °C was cut with a pulsed laser. The pulse was so short that the thermal cycle in the material adjacent to the cut could be modelled by the impulse solution. A thermocouple located 5 mm from the cut recorded a peak temperature of 320 °C at 1.4 s after the pulse. Estimate the thermal diffusivity of the steel and the peak temperature at a distance of 2 mm from the cut. [25%]

(b) For each of the following types of welded joint, discuss possible causes of premature failure of the joint, and suggest ways in which these causes could be reduced or eliminated.

(i) A butt-weld between two thick pieces of mild steel plate, subjected to high static stress in a dry environment. [30%]

(ii) A weld between two pieces of galvanized mild steel plate. [20%]

3 Account for the following service failures and suggest ways in which they might have been avoided.

(a) A batch of HDPE garden chairs failed by cracking after only a few months of use. A piece of the same material which had been exposed to the same environment but not subjected to load suffered only slight reduction in strength in the same time. [20 %]

(b) A large steel I-beam (RSJ) failed suddenly by cracking along the web shortly after the end of the beam had been removed by flame cutting. [20 %]

(c) A weld in unstabilized stainless steel exposed to damp conditions suffered failure in the region close to the weld. [20 %]

(d) A bowl made from cold-worked $\alpha$-brass was cleaned using a proprietary liquid containing ammonia. The bowl subsequently developed cracks. [20 %]

(e) Copper pipes in a hot water central heating system suffered pinhole corrosion after a few months of service. Graphite had been used as a lubricant in the manufacture of the pipes. [20 %]

(TURN OVER

4 (a) Explain the assumptions of the work formula method for estimating forces in metalworking. Define the terms *redundant work* and *efficiency* in the context of deformation processing.

Show that for direct extrusion of a material which obeys the Tresca yield criterion, the work formula method leads to an estimate of the extrusion pressure $p$ given by

$$p = 2\,k \ln R$$

where $R$ is the extrusion ratio (ratio of input area to output area) and $k$ is the yield stress in pure shear. [30%]

(b) Figure 1 shows a possible deformation pattern for plane strain direct extrusion of a slab through a 45° symmetrical die at an extrusion ratio of 4. Shear occurs on planes AB and BC, and AB is perpendicular to the axis of the die. The die can be assumed to be frictionless.

(i) Calculate an upper bound to the extrusion pressure $p$ for a material which is perfectly plastic and has a yield stress in pure shear of 100 MPa.

(ii) Compare the value obtained in (i) to the value derived from a work formula estimate. What is the efficiency of this extrusion process?

(iii) Suggest ways in which this upper bound model might be improved. [70%]

(cont.

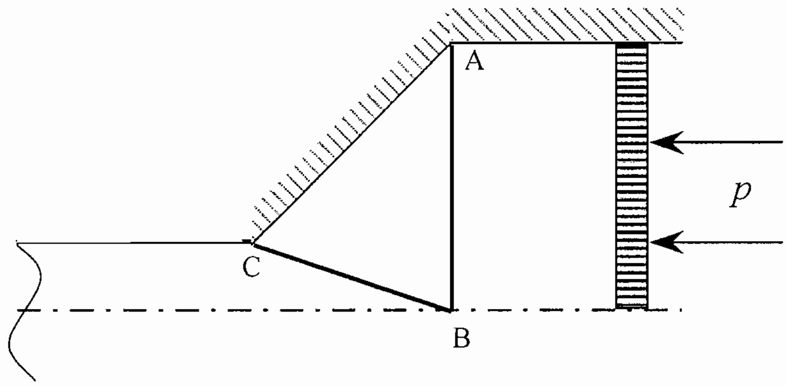


Fig. 1

**END OF PAPER**

**Numerical answers**

**Question 1.**

(b) $n = 2$.

(c) Solutions agree up to approx. $x$ = 5mm.

**Question 2**

(a) (ii) $a = 8.9 \times 10^{-6}$ m$^2$/s. $T_p$ = 770 °C.

**Question 4.**

(b) (i) $p$ = 350 MPa.

(ii) $p$ = 277 MPa Efficiency = 0.79 i.e. 79%.