ENGINEERING TRIPOS PART IIA
MANUFACTURING ENGINEERING TRIPOS PART I

Wednesday 3 May 2006 9 to 10.30

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
Graph paper × 2 sheets

Manufacturing Engineering Tripos:
20 page booklet, rough work pad
Graph paper × 2 sheets

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

1 (a) What is meant by the 'process zone' at a crack tip? Why are process zones smaller in a metal under plane strain conditions than under plane stress conditions? [20%]

(b) The local stress σ_{local} at a distance r ahead of a sharp crack of length a under an applied tensile stress σ is given by

$$\sigma_{\text{local}} = \sigma\left(1 + \sqrt{a/2r}\right)$$

and the von Mises yield criterion states that

$$(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_1 - \sigma_3)^2 = 2\sigma_y^2$$

where the symbols have their usual meanings. Derive expressions for the radius of the process zone under conditions of plane strain and plane stress. [40%]

(c) Explain qualitatively how process zone size influences toughness. [15%]

(d) Use the concept of a process zone to explain:

(i) how one might increase the toughness of an amorphous polymer below its glass transition temperature; and

(ii) why passengers are forbidden to take liquid mercury onto an aircraft. [25%]

2 (a) Discuss the advantage of dimensional analysis when modelling thermal manufacturing processes, giving examples of its applications in this context. [25%]

(b) The surface of a large steel component at an initial temperature T_o is heated with a uniform heat source of intensity $\bar{q}$ (W m^{-2}) from time $t = 0$. The surface temperature rise $[T(t) - T_o]$ may be assumed to depend only on the intensity of the heat source $\bar{q}$, the thermal diffusivity a and the thermal conductivity λ of the steel. Use dimensional analysis to find the governing dimensionless group for this problem. Give an example of a possible application of this result in materials processing. [20%]

(c) Explain the following observations.

(i) A piece of window glass is loaded in bending under humid conditions. After about one day, it fails suddenly by brittle fracture.

(ii) Miner's rule is not an accurate indicator of fatigue lifetime.

(iii) The fatigue lifetimes of structures which are initially uncracked can be very much greater than those which already contain cracks.

(iv) Unstabilised stainless steels are prone to corrosion failure in heat-affected zones around welds. [55%]

3 Figure 1 shows the geometry of a sheet-drawing process. The sheet is reduced in thickness from h_i to h_o by being pulled through a symmetrical die of semi-angle α and corresponding contact length W. The width L of the sheet (measured perpendicular to the plane of the figure) is much greater than h_i. The directions 1, 2 and 3 represent the principal axes of stress and strain in the sheet. All deformations take place in the plane of the figure. The drawing stress at the die outlet is σ_{1o}.

(a) Show that the tensile stress σ_1 along the strip, assumed constant across the strip in the 3 direction, varies through the die according to the following expression:

$$\sigma_1 = \left(\frac{A}{A-1}\right)\left\{1-\left(\frac{h}{h_i}\right)^{A-1}\right\} \sigma_y .$$

Here h is the local thickness of the strip, $A = (1+\mu\cot\alpha)/(1-\mu\tan\alpha)$, μ is the coefficient of Coulomb friction between sheet and dies and σ_y is the uniaxial yield stress. You should use the Tresca yield criterion. [60%]

(b) In an actual sheet-drawing process, $h_i = 3$ mm, $h_o = 2$ mm and $W = 2$ mm. It is found that the process ceases to work if $\mu > 0.7$. Give a quantitative explanation for this observation and discuss practical solutions to overcome the problem. [40%]

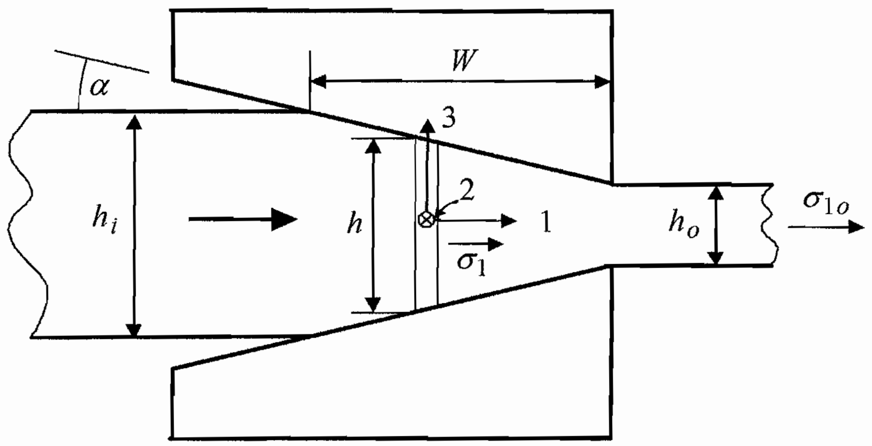

Fig. 1

4 In a forging process, a pair of large flat tool steel dies at an initial uniform temperature of 20 °C are brought into contact at time $t = 0$ with a large steel billet of thickness $2l$ at 900 °C. Sufficient pressure is applied to maintain intimate thermal contact (perfect heat transfer), but without deforming the billet. The purpose of the procedure is to preheat the die surfaces before forging commences. As the billet and dies are much larger than the billet thickness, it is reasonable to assume one-dimensional heat flow from the billet into the dies. The thermal diffusivity a of the billet and dies may be assumed to have the same value.

(a) Write the temperature $T(x,t)$ in the billet and dies in a suitable dimensionless form, and show that the temperature distribution can be expressed in the following form:

$$\frac{T(x,t)-20}{900-20} = \frac{1}{2}\operatorname{erf}\left(\frac{x+l}{2\sqrt{at}}\right) - \frac{1}{2}\operatorname{erf}\left(\frac{x-l}{2\sqrt{at}}\right)$$

Note that the one-dimensional heat flow solution for the temperature in an infinite bar is given by the error function

$$T(x,t) = \operatorname{erf}\left(\frac{x}{2\sqrt{at}}\right)$$

for the case of an initial temperature distribution given by

$$T(x,0) = -1 \qquad (x<0)$$
$$T(x,0) = 1 \qquad (x>0)$$

[65%]

(b) (i) Using the results of part (a), sketch the temperature – log(time) curves for the centre and surface of a slab of thickness 40 mm for $1 \text{ s} \leq t \leq 1000$ s.

(ii) From the sketch or otherwise, estimate the time taken for the difference in temperature between the centre and surface of the slab to fall below 100 °C. The thermal diffusivity of the billet and the dies is $a = 10^{-5}\ \text{m}^2\ \text{s}^{-1}$. Values of the error function may be taken from the Materials Databook. [35%]

END OF PAPER

Engineering Tripos Part IIA: Module 3C2
Manufacturing Engineering Tripos Part I: Paper P4B
Materials process modelling and failure analysis
Numerical solutions - 2005/6

1 (b) Plane stress $r_y = \frac{a}{2}\left(\frac{\sigma}{\sigma_y}\right)^2$, Plane strain $r_y = \frac{a}{2}\left(\frac{(1-2\upsilon)\sigma}{\sigma_y}\right)^2$

2 (b) $T(t) - T_o = C\frac{\overline{q}}{\lambda}\sqrt{a\,t}$

4 (c) Approximately 35 seconds.