ENGINEERING TRIPOS PART IIA
MANUFACTURING ENGINEERING TRIPOS PART I

Thursday 1 May 2003 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.*

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

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1 Explain the following observations. In each case, indicate what could have been done to prevent the failures from occurring.

(i) A welded carbon-steel bath used for containing liquid zinc at 500°C failed after only a few hours in service. The fracture surface showed that the failure had been predominantly intergranular. [25%]

(ii) High-strength steel bolts that had been electroplated with nickel were used for joining plates in a pressure vessel operating at room temperature. Some of the bolts failed as the vessel was pressurised. [25%]

(iii) Electrical plugs made of Noryl (a blend of amorphous polymers) were injection moulded in two parts and assembled by a process involving welding. High stresses often had to be used to produce good welds because one of the parts tended to be distorted. A significant proportion of the plugs supplied to one electrical equipment manufacturer were found to fail after only a short period in service. In all cases, the weld line showed cracking. Investigations revealed that this manufacturer had used an anti-static aerosol spray to clean the plugs before dispatching them to customers. [25%]

(iv) A closed circulating-water heating system was protected against corrosion using an anodic inhibitor added to the water. The system was partially drained for maintenance, following which the water was topped up. Within a few days, pinhole leaks were observed in the system. [25%]

2 (a) Process modelling offers a range of benefits to industrial materials producers. Summarise four reasons for developing a process model, with a brief example in each case. [40%]

(b) Finite element analysis is the standard approach to thermal and thermo-mechanical process modelling in industry. Describe, with examples, the advantages of using this numerical method compared to analytical methods. [30%]

(c) Steels are sometimes shot-peened to increase their resistance to fatigue failure. Explain why this process results in residual stresses in the material, and why improved fatigue resistance is achieved. When shot-peened steels fail, explain where cracks would be expected to form, and why. [20%]

(d) Butt-welded joints are sometimes machined to change their profile before being put into service, often by grinding. Why is this done? Why is the direction of grinding important? What other mechanical treatments can be carried out to improve the performance of such welds? [10%]

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3 In a plane strain drawing operation, an aluminium-copper alloy sheet is reduced from thickness h_i to thickness h_o by drawing through a rough die with half angle α , as shown in Fig. 1.

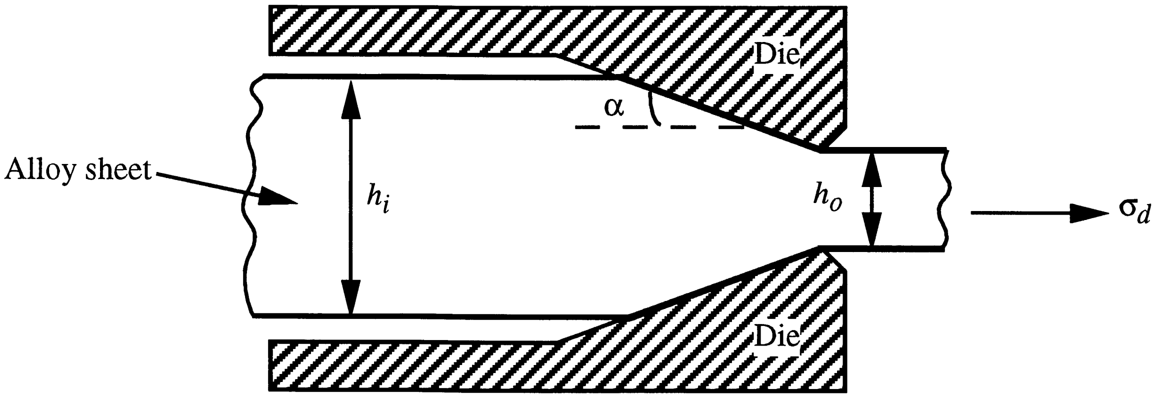

Fig. 1

The draw stress σ_d can be estimated by an equilibrium analysis as;

$$\sigma_d = Y\left(1 + \frac{\tan\alpha}{2} + \frac{\cot\alpha}{2}\right)\ln\left(\frac{h_i}{h_o}\right)$$

where Y is the uniaxial yield stress. Data for the alloy are given below.

(a) Outline the steps in the analysis, but do not derive the equation. State carefully the assumptions on which the analytical result is based. What alternative assumptions could have been made and how would these affect the result? [40%]

(b) Explain how the analytical result could be used to estimate the ram force F per unit depth into the page for an extrusion, rather than a drawing, operation. For what value of the die angle α_{min} is the extrusion ram force minimised? [20%]

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(c) If a "square die" ($\alpha = 90°$) is used, the analytical result gives an unrealistic estimate of extrusion ram force F. Explain why, in this case, using the analytical result with $\alpha = \alpha_{min}$ gives a more reasonable estimate of F. Hence estimate the ram force per unit depth required to extrude a billet of thickness 25 mm and produce a sheet of thickness 10 mm in this alloy, using a square die. Why could this thickness reduction not be carried out by drawing? [20%]

(d) To what temperature should the 25 mm billet be pre-heated if the extrusion operation is required to solutionise the alloy at 550°C ? State the assumptions you make and comment on their likely accuracy if the extruded sheet is to be produced at a rate of 20 mm s^{-1}. [20%]

Data for aluminium-copper alloy during hot working: Uniaxial yield stress, $Y = 255$ MPa, Heat capacity, $\rho c_p = 2.6$ MJ m^{-3} K^{-1}, thermal diffusivity, $a = 46 \times 10^{-6}$ m^2 s^{-1}.

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4 A prototype laser welding process for making lap-joints in polymers is illustrated in Fig. 2. The polymer is transparent to the laser wavelength, and a fraction A of the incident power Q is absorbed at the interface via a pre-deposited dye. The defocused laser irradiates a circular spot of radius r_B, which is traversed along the joint at a speed v. Successful welding requires that a thin melt layer just forms at the interface.

Heat flow is essentially one-dimensional for depths below the interface that are small compared to the beam radius. For low conductivity materials it is also sufficient to employ the solution for a *stationary* heat source applied for a time τ equal to the beam interaction time $2r_B/v$.

When a laser producing a uniform power density heats the surface of a semi-infinite solid for a time τ, the peak temperature T_p at a depth z below the surface is well-approximated by:

$$T_p - T_0 = \frac{\dfrac{2\overline{q}\sqrt{a\tau}}{\lambda\sqrt{\pi}}}{1 + \dfrac{z\sqrt{\pi}}{2\sqrt{a\tau}}}$$

where T_0 is the initial temperature, $\overline{q}$ is the absorbed power density and λ and a are the thermal conductivity and diffusivity, respectively.

(a) Explain why, for the polymer welding process, the appropriate power density to use is: $\overline{q} = \dfrac{AQ}{2\pi r_B^2}$. [15%]

(b) Use the solution given to find an expression for the peak temperature as a function of depth, for the problem of the polymer welding process, and re-arrange this into dimensionless form:

$$q^* = f(v^*, z^*)$$

where $q^* = \dfrac{AQ}{r_B\,\lambda(T_p - T_0)}$, $v^* = \dfrac{v\,r_B}{a}$ and $z^* = \dfrac{z}{r_B}$.

Derive a second dimensionless expression for the ratio of the peak temperatures at the surface and at a given depth. [30%]

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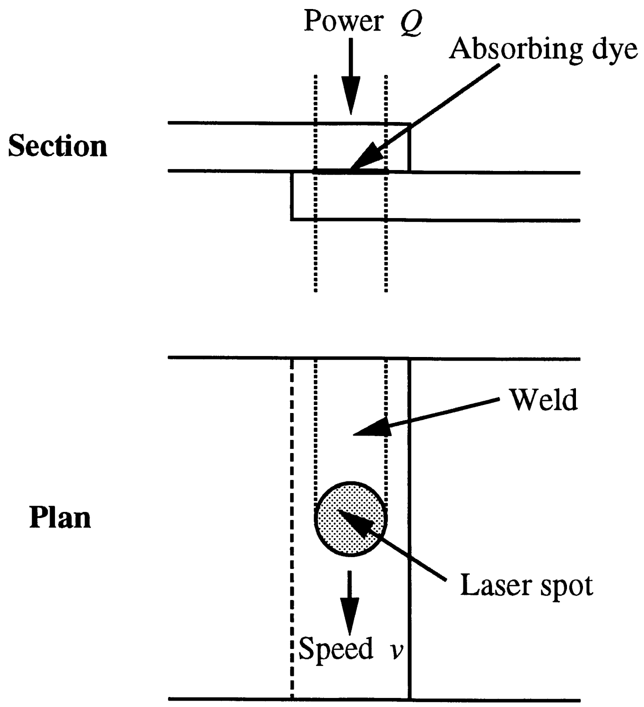
(c) A trial weld was conducted with the conditions given below to join two strips of PET with the material properties also given below, where T_m and T_g are the melting and glass transition temperatures of the polymer, respectively. Determine the dimensionless melt depth, and hence find the thickness of the melt layer at the interface. Calculate the peak temperature at the interface for this weld. [30%]

(d) Examination of the weld in cross-section under polarised light revealed a heat-affected zone of depth 220 μm. Find the peak temperature rise at this depth, and comment on the possible reason for the formation of the heat-affected zone, given that the as-received material was initially drawn into a thick sheet. [25%]



Process conditions:
Q = 120 W
v = 0.08 m s^{-1}
r_B = 2 mm
A = 0.1
T_0 = 20°C

Material properties:
λ = 0.145 W m^{-1} K^{-1}
a = 8.2×10^{-8} m^2 s^{-1}
T_m = 250°C
T_g = 75°C

Fig. 2

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