ENGINEERING TRIPOS PART IIA
MANUFACTURING ENGINEERING TRIPOS PART I

Thursday 29 April 2004 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.

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) A fence has been constructed for a recreation area. Untreated mild steel has been used for the posts and bars, and these were painted when the fence was first erected. The fence is often damp, as a result not only of the climate, but also the sprinkler used for the grass in summer. Due to an administrative dispute, the Council has failed to paint the fence since its erection. It now shows considerable signs of corrosion.

The angle-iron vertical posts are set into concrete bases. The horizontal bars are made from the same steel, and are tack-welded to the vertical posts. A commemorative brass plaque has been attached to one part of the fence using brass bolts. Elsewhere, a wooden notice requesting that dogs be prevented from fouling the grass has been attached using twists of mild steel wire.

(i) The following localised corrosion effects were observed at various parts of the structure: crevice corrosion; differential energy corrosion; bimetallic corrosion. Identify all the areas where you would expect to find these. Give full explanations for the effects, with equations where relevant. [40%]

(ii) The bases of the posts were also observed to be badly corroded. Explain this effect. [10%]

(b) (i) Briefly describe the benefits of coupling a model for microstructural evolution with a conventional thermal or thermo-mechanical process model. [20%]

(ii) Outline what is meant by an *internal state variable* model for microstructural evolution. Give an example of a phenomenon in metals processing which may be described by a single state variable. Why can it be advantageous to have a single state variable in modelling microstructural change in a transient thermal cycle? [30%]

2 (a) It is proposed to conduct a finite element analysis of a quenching problem in the heat treatment of a steel component. Summarise the factors which must be considered to produce an efficient, accurate solution, including both construction of the model and the data required. [20%]

(b) An analytical solution to the variation of temperature T in the Jominy end-quench test with time t and position x from the quenched end is:

$$T(x,t) = T_0 + (T_1 - T_0)\ \mathrm{erf}\left(\frac{x}{2\sqrt{a\,t}}\right)$$

where T_1 is the initial uniform temperature of the specimen, T_0 is the temperature of the quenching water (assumed constant) and a is the thermal diffusivity of the test material.

(i) Summarise the modelling approximations and boundary conditions assumed in deriving this result. [15%]

(ii) Find the cooling rate $\dfrac{\partial T}{\partial t}$ in terms of T_0, T_1, X and t, where

$$X = \left(\frac{x}{2\sqrt{a\,t}}\right).$$

Hence, by using a suitable approximation to the error function erf(X), derive an expression for the cooling rate at a fixed temperature T, in terms of T_0, T_1, X and t. It may be assumed that $T < (T_1 + T_0)/2$. [40%]

(iii) A steel Jominy specimen is quenched from an initial temperature of 1000 °C, using water at a temperature of 20 °C. Find the cooling rate at a distance $x = 5$ mm from the quenched end at a temperature $T = 500$ °C. The steel has thermal diffusivity $a = 1.2 \times 10^{-5}\ \mathrm{m^2 s^{-1}}$. [10%]

(c) Explain why the analytical solution gives a good approximation to the cooling history near the quenched end of a Jominy end-quench specimen, but significantly over-estimates the cooling time for the specimen, compared with experimental observations and valid finite element analyses. [15%]

3 A series of raised ridges is to be produced on a copper plate of thickness a by a plane-strain cold forging operation. Figure 1 shows a cross-section through part of the rigid tooling and the workpiece. There is zero strain perpendicular to the plane of the figure. An upper die, marked U in Fig. 1, is pressed into the plate by uniform pressure p on its upper surface. The upper die has a series of teeth of width a, separated by gaps of width λa. A possible deformation mechanism is shown, with blocks labelled A to H separated by planes of intense shear. The pattern of deformation is repeated along the workpiece. Blocks A, D and H are assumed not to slip relative to the adjacent tooling surfaces.

(a) Die U is moved downwards with velocity v while the lower die O remains fixed. By considering the mechanism shown in Fig. 1, construct a hodograph (velocity diagram) showing the velocity of material in the blocks A to H. [30%]

(b) Show that an upper bound on the forging pressure p is given by

$$p = \left(\frac{\lambda^2 + 3\lambda + 2}{\lambda(1+\lambda)} \right) k$$

where k is the shear flow stress of the copper. [35%]

(c) Find upper bound values of p/k when:

(i) λ is much less than 1;

(ii) λ is much greater than 1.

Comment on the expected accuracy of these upper bound values as an estimate of the forming load. [25%]

(d) Suggest a suitable alternative forming process by which the ridged plate could be produced with reduced tooling loads. [10%]

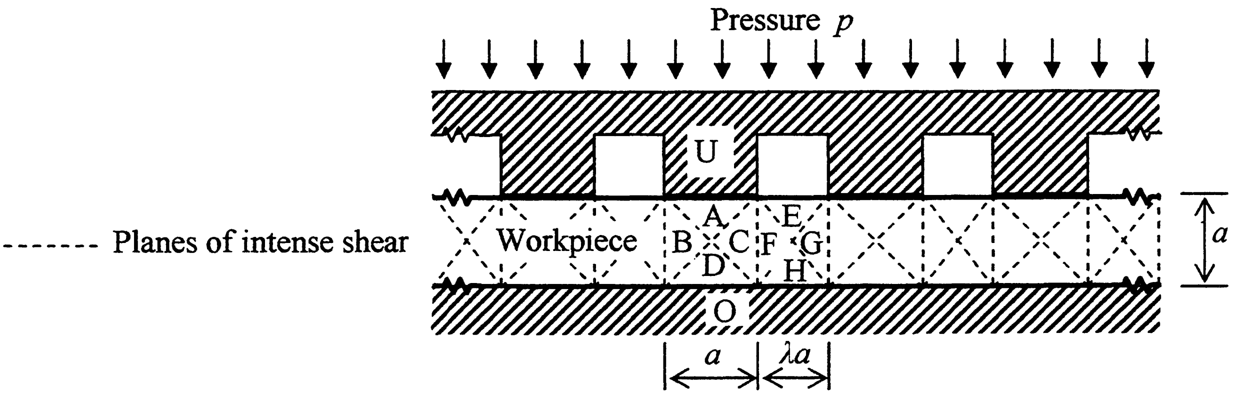

Fig. 1

4 (a) (i) Explain why notched samples of ferritic steels undergo a ductile-brittle transition as the temperature is reduced. Why do austenitic steels not show this behaviour? With the aid of diagrams indicating the variation with temperature of yield stress and fracture toughness, show why ferritic steels of different thicknesses exhibit the transition at different temperatures. [30%]

(ii) Discuss qualitatively the differences between the ductile-brittle transition temperatures in the following pairs of samples of ferritic steel:

- Impact specimens with and without notches;
- Annealed and cold-deformed specimens. [15%]

(b) (i) Tensile specimens of austenitic steel of thicknesses ranging from 'very thin' (0.5 mm) up to 'thick' (30 mm) are strained to failure. Sketch the main features of the three types of fracture surfaces you would expect to see, and account for the differences. Sketch a typical fracture-toughness versus thickness curve for a ductile metal, indicating where your fracture surfaces would be found. What fracture surface would be typical of a specimen used to measure the fracture toughness K_{IC} ? [40%]

(ii) Sketch the fracture-toughness versus thickness curve for a polymer such as polycarbonate. Account for any differences between this curve and the curve for the ductile metal. [15%]

END OF PAPER