ENGINEERING TRIPOS PART IIA
MANUFACTURING ENGINEERING TRIPOS PART I

Wednesday 4 May 2005 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

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1 (a) A seat is to be installed at a beauty spot on a section of mountain road. It is required to meet certain minimum standards of strength and toughness over a ten-year lifetime. Temperatures vary between –30 ºC and +40 ºC, and the area suffers precipitation on a daily basis and frequent high humidity. Long-fibre GFRP has been proposed as a candidate material; there is a choice of two alternative matrix materials: PVC and PP. Two series of accelerated ageing tests have been performed on the materials. One batch of each of the composites has been immersed in water at 40 ºC. A second batch has been kept dry, but has been subjected to temperature cycles between –30 ºC and +40 ºC.

Reference may be made to the Materials Data Book, particularly tables II.1 and II.6. The thermal expansion coefficients, α, of PVC and PP are both 10^{-4} ºC^{-1}; α for glass is 10^{-6} ºC^{-1}.

(i) Describe all the types of degradation you might expect to occur in service, and indicate the expected effect on the mechanical properties of the materials. Will there be any differences between the two GFRP materials? [40%]

(ii) Discuss whether the results of the accelerated ageing tests are likely to provide the necessary data to assess whether the seat will meet the required standards. If not, suggest what conditions the tests should simulate. [15%]

(iii) Which of the two proposed composites would you recommend, and why? [10%]

(b) A low-alloy ferritic steel used in a steam turbine for electricity generation showed brittle intergranular fracture after one year in service at 400 ºC. An alloy of the same composition in another turbine operating under similar conditions showed no signs of failure. On analysis, the grain size was found to be larger by a factor of five in the turbine which had failed. Explain these observations. [20%]

(c) A structural member made from peak-aged precipitation-hardened aluminium alloy has been used in marine conditions, and has failed prematurely. The fracture surface has been examined, and appears to show brittle failure. Samples of similar material tested away from the marine environment failed in a ductile manner. Discuss the likely cause of the premature failure. [15%]

2 (a) The thermal cycle $T(t)$ (i.e. temperature as a function of time) in steel welding may often be modelled using the thick plate Rosenthal solution for a point source of heat:

$$T(t) - T_0 = \frac{(q/v)}{2\pi\lambda t} \exp\left(-\frac{r^2}{4at}\right)$$

The weld power and traverse speed are q and v respectively, T_0 is the ambient temperature, r is the radial distance from the heat source in the plane normal to the weld, and λ and a are the thermal conductivity and diffusivity of the steel, respectively.

(i) Find an expression for the time t_p to reach peak temperature, and hence show that for times much greater than this the exponential term in the solution for $T(t)$ tends to unity. Assume now that the peak temperature is high enough that this will be valid during cooling for $T < 900$ °C. Hence find an expression for Δt_{8-5}, the time taken to cool from 800 °C to 500 °C. [40%]

(ii) These heat flow solutions have been used in failure analysis of microalloyed steel welds, such as those that have occurred in offshore oil rigs. Outline briefly the key microstructure evolution models that need to be combined with the thermal models in order to understand and predict the origins of weld failures originating in the heat-affected zone. [20%]

(b) A small galvanised steel plate has been welded on to a mild steel pressure-vessel, to cover a full-thickness crack in the wall of the pressure-vessel. Fillet welds around the full perimeter of the small plate have been used. The vessel contains dry gas at room temperature, at variable pressure.

(i) Where would you expect failure to occur? How can the likelihood of failure be reduced by post-weld treatment? [20%]

(ii) The pressure vessel is now declared unsafe for pressure use, and is used to contain water at 80 °C. What additional problems might be encountered? [20%]

3 (a) In the analysis of heat treatment of steels, the dimensions of components of different geometries often need to be correlated in terms of "the same cooling rate" at critical locations. Explain the purpose of finding a correlation of this type. [15%]

(b) A correlation is to be found between the distance along a Jominy bar, and the thickness of a slab, for the same cooling rate $\partial T / \partial t$ at the slab centre and at a distance z from the quenched end of the Jominy bar.

The cooling rate in a Jominy test, assuming perfect heat transfer at the quenched end and a semi-infinite bar, is given approximately by:

$$\frac{\partial T}{\partial t} \approx -\frac{(T-T_0)}{\sqrt{\pi}} \left(\frac{C^2\, 4a}{z^2} \right) \exp\left(-C^2\right) \quad \text{where} \quad C = \frac{T-T_0}{T_1-T_0} \ .$$

The initial, current and ambient temperatures are T_1, T and T_0 respectively, and a is the thermal diffusivity of the steel.

For quenching of a large slab of thickness 2ℓ, assuming perfect heat transfer, the temperature of the slab at time t is given by:

$$\frac{T(x,t) \;-\; T_0}{T_1 \;-\; T_0} = \frac{4}{\pi} \exp\left(-\frac{\pi^2 a\, t}{4\, \ell^2} \right) \cos\left(\frac{\pi\, x}{2\, \ell} \right)$$

where the through-thickness position x is measured from mid-thickness, and the other parameters are as defined above. This solution is valid provided $(a\,t / \ell^2) > 0.2$.

(i) Derive an expression for the cooling rate $\partial T / \partial t$ at the slab centre in terms of $(T - T_0)$, a, and ℓ. [30%]

(ii) Show that the slab thickness 2ℓ is proportional to the Jominy distance z, for the same cooling rate at a given temperature. Find the constant of proportionality for the following temperature conditions: T_1 = 840 °C, T = 500 °C and T_0 = 20 °C. Hence find the thickness of slab subjected to a perfect quench which has the same cooling rate at its centre as a point 25 mm from the end of a Jominy bar. [35%]

(iii) Explain why the correlation between thickness 2ℓ and z is not unique. Briefly describe one other definition of "the same cooling rate" which is used in practical heat treatment of steels. [20%]

4 A long bar is compressed between flat dies. The bar has a rectangular cross section, with cross-sectional width $2w$ and height $2h$. The forging force per unit length F/D can be estimated as:

$$\frac{F}{D} = Yw\left(2 + \mu\frac{w}{h}\right)$$

where μ is the coefficient of friction at the interface between the workpiece and the tooling and Y is the uniaxial yield stress of the workpiece material.

(a) Outline the steps in this analysis, stating carefully any assumptions that are made. There is no need to derive the result. [25%]

(b) By using an analogy between forging and rolling, find an expression for the rolling torque required at each work roll to reduce a wide strip of material of width D from initial thickness t_i to outlet thickness t_o between rolls of radius R. The coefficient of friction is μ and you may assume that $t_i - t_o \ll R$. [20%]

(c) State three ways in which the rolling torque may be reduced in a practical rolling operation. In each case, state a disadvantage of the proposed method and give measures that may be taken to overcome the disadvantage. [30%]

(d) In a final cold rolling operation to produce aluminium alloy foil, work rolls of diameter 8 mm are used to reduce the foil thickness from t_i = 0.11 mm to t_o = 0.10 mm. The strip width D = 900 mm and the foil is produced at 900 m per minute. The torque applied to each work roll is 2.5 N m.

The following data apply for this aluminium alloy; uniaxial yield stress Y = 115 MPa, heat capacity ρc_p= 2.6 MJ m^{-3} K^{-1}, thermal diffusivity $a = 46 \times 10^{-6}$ m^2 s^{-1}.

(i) Estimate the *mean* temperature rise in the foil during rolling, stating any assumptions that you make. [15%]

(ii) Explain, without doing any calculations, how you might estimate the *surface* temperature rise during rolling. [10%]

END OF PAPER