

EGT1  
ENGINEERING TRIPOS PART IB

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Monday 10 June 2024 2 to 4.10

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**Paper 3**

**MATERIALS**

*Answer not more than **four** questions, which may be taken from either section.*

*Answers to questions in each section should be tied together and handed in separately.*

*All questions carry the same number of marks.*

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

*Write your candidate number **not** your name on the cover sheet.*

**STATIONERY REQUIREMENTS**

Single-sided script paper

**SPECIAL REQUIREMENTS TO BE SUPPLIED FOR THIS EXAM**

CUED approved calculator allowed

Engineering Data Book

**10 minutes reading time is allowed for this paper at the start of the exam.**

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

**You may not remove any stationery from the Examination Room.**

**SECTION A**

- 1 (a) (i) For a constant pressure, sketch on the same graph the Gibbs free energy of the liquid and solid phases of a pure substance as a function of temperature. On the sketch, indicate the equilibrium melting temperature,  $T_m$ , and the stability domains of the liquid and solid phases. [3]
- (ii) Stating any assumptions, show that the Gibbs free energy of solidification per unit volume,  $\Delta G$ , is proportional to the undercooling. [3]
- (b) Explain the difference between interstitial and substitutional solid solutions, and give one example of each. With the help of appropriate sketches, describe the mechanisms by which each type of solute diffuses through a single crystalline solid alloy, and explain how this leads to the concept of an activation energy,  $Q$ , for diffusion. Which of these diffusion mechanisms generally results in faster diffusion, and why? [9]
- (c) (i) Using a *single crystal* sample of Cu–30 wt% Zn, the diffusion coefficient,  $D$ , of zinc in copper was measured experimentally, and the results are shown in Table 1. Use these data to determine the activation energy  $Q$ . [6]

	Single crystal	Polycrystalline
$T$ (°C)	$D$ ( $\text{m}^2\text{s}^{-1}$ )	$D$ ( $\text{m}^2\text{s}^{-1}$ )
330	$8.2 \times 10^{-22}$	$9.1 \times 10^{-18}$
730	$3.6 \times 10^{-15}$	$3.8 \times 10^{-15}$

Table 1

- (ii) In a *polycrystalline* sample of Cu–30 wt% Zn,  $D$  was measured as shown in Table 1, 3rd column. Explain the effect of microstructure on  $D$ . [4]

2 (a) State the thermodynamic condition for oxidation to occur. Explain qualitatively why the rate of growth of the oxide layer changes with time. Under what circumstances might a metal show a linear rate of oxidation? [6]

(b) A cylindrical copper bar of length 100 mm and diameter 10 mm is heated, in air, for 1 hour such that an oxide film grows on its surface. One end is held at 400 °C and the other end at 500 °C in order to develop a linear temperature profile along the bar's length. Figure 1 shows the thickness of the resulting oxide measured every 20 mm along the bar length.

(i) If the density of the oxide layer is  $6 \text{ Mg m}^{-3}$ , show that the total mass of oxide present on the bar is  $\approx 17 \text{ mg}$ . [8]

(ii) Assuming parabolic growth of the oxide thickness with time, after what length of time would 85 mg of oxide have formed? [4]

(iii) Show graphically that the data in Fig. 1 follow the Arrhenius law, and calculate the activation energy  $Q$ . [7]

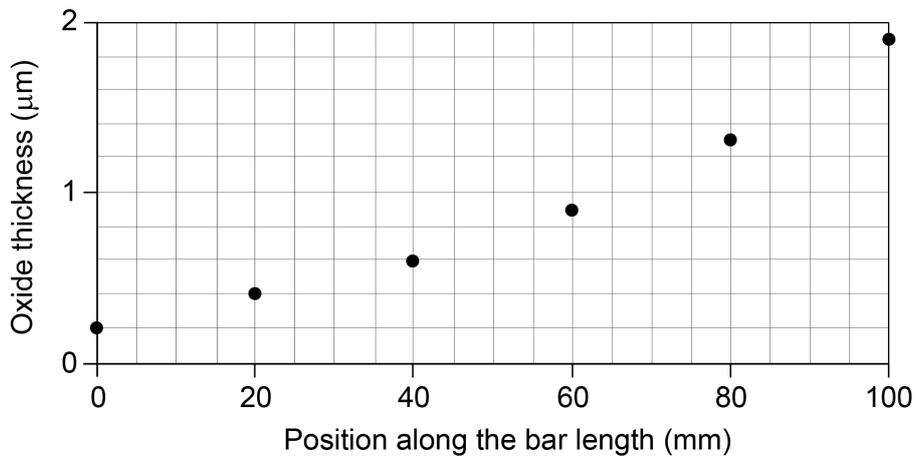


Fig. 1

3 A set of samples of annealed brass were cold rolled to reductions in thickness between 0% and 60%. Tensile tests were then conducted on the rolled material, to find the resulting yield strength and ductility after cold work. Figure 2 shows the collated data, with best fit curves through the datapoints.

(a) A 1.34 mm thick sheet of annealed brass is to be cold rolled to a final thickness of 0.8 mm. The rolled sheet must meet the following final property specification: yield strength > 325 MPa, and ductility > 14%.

(i) Use Fig. 2 to explain why the required reduction cannot be applied in a single pass. [3]

(ii) If two rolling passes are used, with an intermediate annealing step, find the upper and lower limits for the reduction that must be applied in the *second* pass, in order to meet the final property specifications. Hence, for each limit, find the corresponding sheet thickness between the passes, and the % reduction in the first pass. [6]

(iii) In an alternative two-step rolling schedule, the % reduction is set to be the same in each pass. Find the intermediate sheet thickness between the passes, and the final yield strength and ductility of the sheet. [5]

(b) The data in Fig. 2 were used to fit an approximate true stress-strain response for annealed brass, giving the equation

$$\sigma = 180 + 380\varepsilon^n$$

where  $\sigma$  and  $\varepsilon$  are the true stress (in MPa) and true strain, respectively, and  $n$  is a constant equal to 0.3.

(i) Convert the % reduction after the first pass in part (a)(iii) to true strain, and hence find the corresponding true stress. [2]

(ii) Integrate the true stress-strain response to this strain, to find the plastic work done per unit volume in the rolling process. [4]

(iii) A small fraction of the work done (5%) is assumed to be stored within the microstructure in the form of dislocations. What happens to the remainder? Estimate the dislocation density in the brass after the first rolling pass, noting that the energy stored per unit length of dislocation is equal to  $Gb^2/2$ , where the shear modulus  $G = 33$  GPa and the Burgers vector  $b = 0.275$  nm. [5]

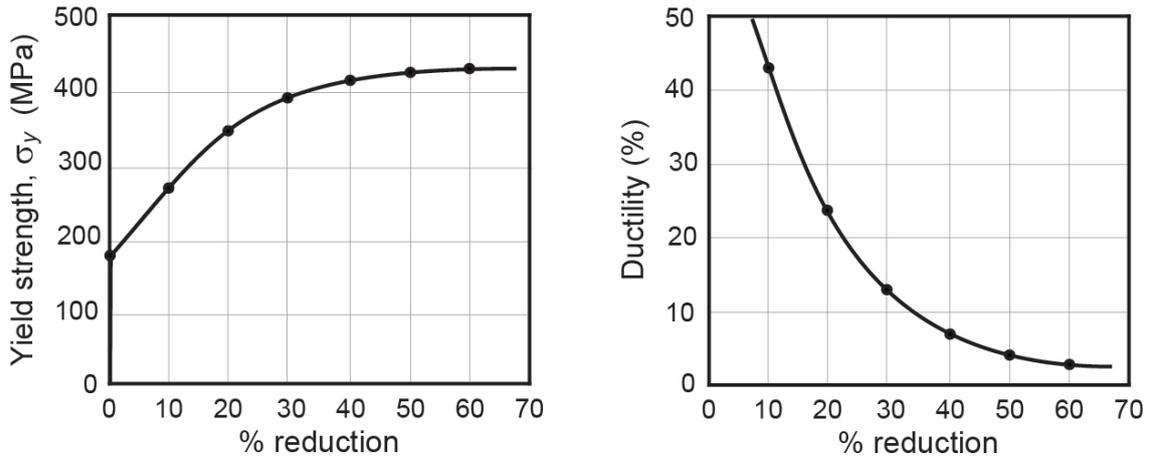


Fig. 2

**SECTION B**

4 (a) Explain briefly what is meant by the *hardenability* of a steel. [2]

(b) Figure 3(a) shows the *Jominy end-quench test* for hardenability. A steel bar is austenitised at a temperature  $T_1$ , and then suspended vertically and quenched on its lower end with water at a temperature  $T_0$ . Assuming one-dimensional heat flow with perfect heat transfer only to the water, the solution for the temperature history  $T(x,t)$  at a distance  $x$  from the quenched end may be adapted from the solution for quenching the surface of a semi-infinite plate. In dimensionless form, this is

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

where  $\operatorname{erf}(X)$  is the error function and  $a$  is the thermal diffusivity of the steel. Note that for  $X < 0.7$ , the error function may be approximated by  $\operatorname{erf}(X) \approx X$ .

(i) For a Jominy bar of length  $L$ , over what heat-flow timescale would it be valid to use the error function solution? [2]

(ii) Use the approximation to the error function for  $X < 0.7$  to find an expression for the time  $t_r$  taken to reach a reference temperature  $T_r$  at a given  $x$ , after the temperature has fallen by  $> 30\%$  of the cooling interval, as shown schematically in Fig. 3(b). [3]

(iii) A representative cooling rate may be found using the time taken to cool between two reference temperatures,  $T_{r1}$  and  $T_{r2}$ , at a given  $x$ . Find an expression for this quantity, and sketch the variation of cooling rate with  $x$ . [4]

(iv) A steel Jominy sample is end-quenched from an initial uniform temperature of  $1000^\circ\text{C}$ , using water at a temperature of  $20^\circ\text{C}$ . The proposed reference temperatures are  $700^\circ\text{C}$  and  $500^\circ\text{C}$ . Briefly explain the relevance of these temperatures in this context. Find the average cooling rate in this temperature interval, for distances of 1 mm and 30 mm from the quenched end. The thermal diffusivity of the steel is  $10^{-5} \text{ m}^2\text{s}^{-1}$ . [5]

(v) After cooling in a Jominy test, the hardness is measured as a function of distance along the bar. Figures 7.2 and 7.4 in the Materials Databook show examples, for a plain carbon steel and a low alloy steel, respectively. Account for the hardness values in each steel at distances of 1 mm and 30 mm from the quenched end, in terms of the microstructure. Which steel has the higher hardenability? [4]

(c) An experiment was conducted to use the Jominy end-quench test to investigate the response of a heat-treatable Al alloy to quenching and ageing. An Al sample of identical size to the steel was end-quenched from an initial uniform temperature of 565 °C. After cooling, the Al sample was held at a uniform temperature of 185 °C for 5 hours. Sketch the expected hardness profiles with distance from the quenched end, in the as-cooled condition and after subsequent ageing. Briefly explain the shape of the curves in terms of the expected microstructures. [5]

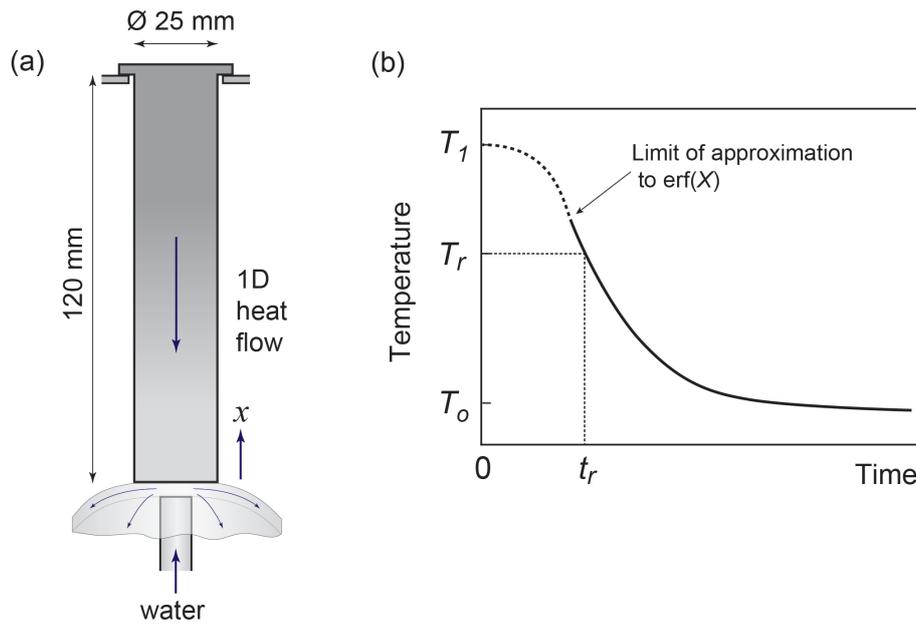


Fig. 3

5 (a) Consider the following cooling treatments from 900 °C to room temperature in medium carbon steel:

- (i) normalisation;
- (ii) quenching.

In each case, describe the atom-scale mechanisms of microstructure evolution, identifying key temperatures and the phases involved, and illustrating your answers with sketches. [10]

(b) Figure 4 shows a property chart of fracture toughness against yield stress, including data for two normalised plain carbon steels, A and B, containing 0.2 wt% and 0.6 wt% C, respectively. Suggest likely values of both properties for 0.4 wt% C after the following heat treatments, explaining your reasoning in terms of the expected phases and microstructures:

- (i) normalised;
- (ii) quenched;
- (iii) quenched and tempered. [9]

(c) Figure 4 also shows the properties of three other ferrous alloys, X, Y and Z. Identify, with reasons, which of these corresponds to the following: stainless steel, quenched and tempered high alloy steel, grey cast iron. Suggest a typical application for each alloy, identifying in each case a design requirement other than mechanical performance that would be critical in selecting this alloy. [6]

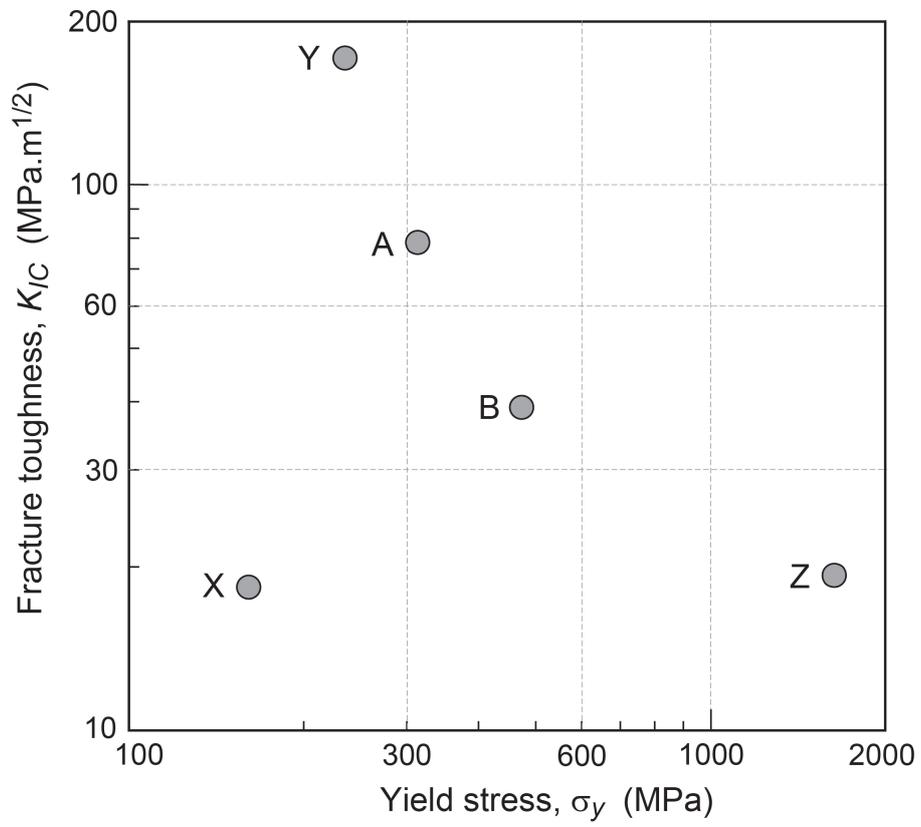


Fig. 4

6 Figure 5 shows the Cu-Ag equilibrium phase diagram.

- (a) (i) Identify the phase(s) in the fields marked A-F. [3]
- (ii) Name the curves labelled X and Y, and explain their significance on cooling. With reference to these lines, as appropriate, explain briefly what is meant by *segregation*. [4]
- (b) (i) Describe the microstructural changes that occur when a Cu-90 wt% Ag alloy is cooled slowly to room temperature from the melt. Illustrate your answer with selected sketches of the microstructure, indicating the corresponding temperatures. [10]
- (ii) What differences in microstructure and mechanical properties would you expect to see if you subsequently annealed the alloy at 450 °C for 3 hours, and cooled slowly back to room temperature? [2]
- (c) (i) What does the point labelled J on Fig.5 indicate? Explain why this composition is particularly important in casting. [3]
- (ii) What does the point labelled K on Fig. 5 indicate? Explain the relevance of this composition to the hardening potential in Ag-rich alloys containing Cu. [3]

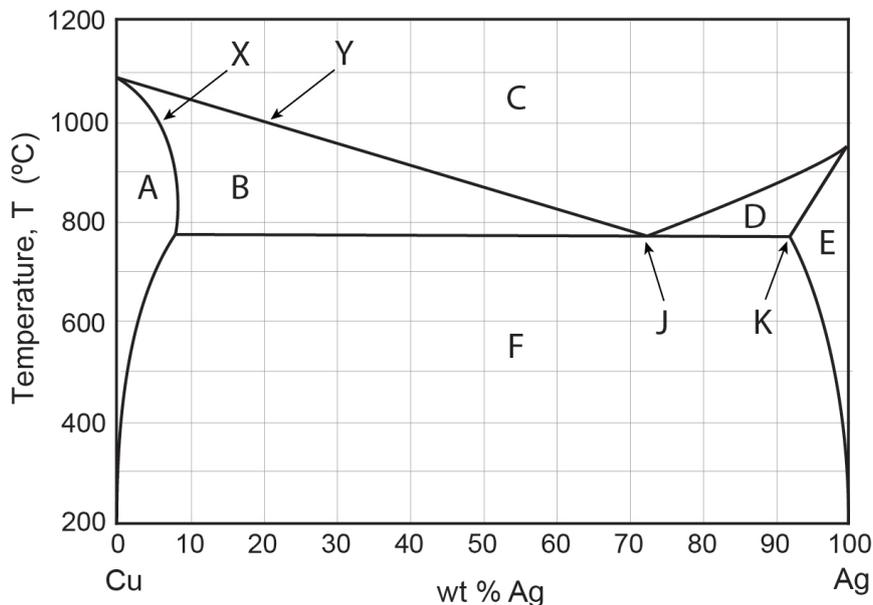


Fig. 5

**END OF PAPER**