

EGT1  
ENGINEERING TRIPOS PART IB

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Monday 3 June 2019 9 to 11.10

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**Paper 3**

**MATERIALS**

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

*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.**

## SECTION A

1 The Cr-Ni phase diagram is shown in Fig. 1. There are three single phase regions, one liquid and two solid. The relative atomic weights of Cr and Ni are 52.0 and 58.7, respectively.

(a) A Cr-Ni alloy of eutectic composition is cooled from the liquid state.

(i) Identify the composition of the alloy (in at% Ni) and its temperature at the eutectic point. [3]

(ii) Identify the phases present, their compositions (in at% Ni) and their proportions *by weight* at a temperature just below the eutectic point. [5]

(b) An alloy of composition Cr-20 at% Ni is cooled slowly from 1800 °C to 800 °C. Describe the phase changes that occur during cooling, using sketches of the microstructure at key temperatures to illustrate your answer. [8]

(c) Sketch the variation in Gibbs free energy with composition (in at% Ni) of the liquid phase and the two solid phases at the following temperatures:

(i) The melting temperature of pure Cr. [3]

(ii) The melting temperature of pure Ni. [3]

(iii) 1000 °C [3]

In each case, indicate how the three curves relate to each other, and identify any key points.

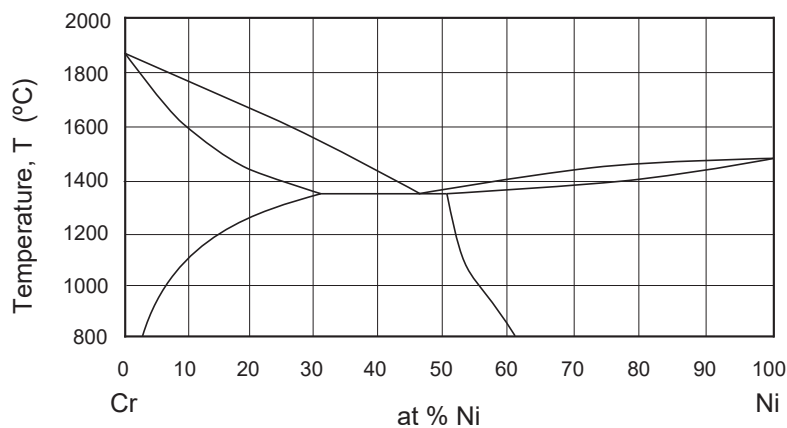


Fig. 1

2 (a) Pure aluminium is cooled from the liquid state to room temperature.

(i) The Gibbs free energy is given by  $G = H - TS$ , where  $H$  is the enthalpy,  $T$  is the temperature and  $S$  is the entropy. Show that the difference in Gibbs free energy between the liquid and solid phases ( $\Delta G$ ) at a given temperature below the melting temperature  $T_m$  is given by

$$\Delta G = \Delta H \frac{(T_m - T)}{T_m}$$

where  $\Delta H$  is the enthalpy difference between the phases. [4]

(ii) A spherical nucleus of solid aluminium of radius  $r$  forms homogeneously within the liquid aluminium. There is an interface energy  $\gamma$  (per unit area) between the solid and liquid phases. Derive an expression for the minimum radius  $r^*$  for a stable nucleus. [6]

(iii) Without further calculation, explain why the rate of solidification is a maximum at a specific level of undercooling ( $T_m - T$ ). [5]

(b) A cast component is to be manufactured using an Al-Si alloy. The Al-Si phase diagram is given in the Materials Data Book.

(i) Explain how alloying Al with Si can influence its processibility and properties, for a near net shape casting application. [3]

(ii) An alloy with composition Al - 5 wt% Si is cooled from the liquid state to room temperature in a large mould. Explain what is meant by segregation during solidification of an alloy, and how segregation might develop across different length scales within the solid. [5]

(iii) How can the casting process be modified to reduce segregation? [2]

3 A closed die forging process is shown in Fig. 2: a metal block of initial width  $w_0$  and initial height  $h_0$  is pressed between flat, rigid dies by applying a force  $F$  per unit length out-of-plane. The out-of-plane dimension of the block is much larger than  $w_0$  and  $h_0$ , so plane strain deformation can be assumed.

(a) Discuss briefly two advantages of deformation processing compared to casting for shaping this metallic component. Give two factors that might limit the suitability of a metal alloy for this deformation process. [6]

(b) The metal block can be assumed rigid-perfectly plastic, deforming at a constant true stress  $Y$  in plane strain compression. Frictionless conditions can be taken between the block and the rigid dies. The block is to be compressed until it fills the space between the rigid dies, which has width  $D$ .

(i) The metal block can be assumed to deform at constant volume. Explain why this is justified from a microstructural perspective. [2]

(ii) Derive an expression for the variation in the forging force  $F$  with the height  $h$  of the block, as it is compressed from its initial height  $h_0$  to its final height. Sketch your solution marking any salient values. [5]

(c) Now, Coulomb friction is to be assumed between the metal block and the dies during the plane strain forging process described in part (b).

(i) Without further calculation, indicate on your sketch for part (b)(ii) how the variation in the forging force  $F$  with the height of the block would change with the addition of friction. Explain any differences. [4]

(ii) The equilibrium method can be used to analyse the spatial variation in the contact pressure between the block and the dies for a given block height. Summarise the analysis steps that would be required and state any assumptions. Note that the derivation of an expression for the contact pressure is not required. [8]

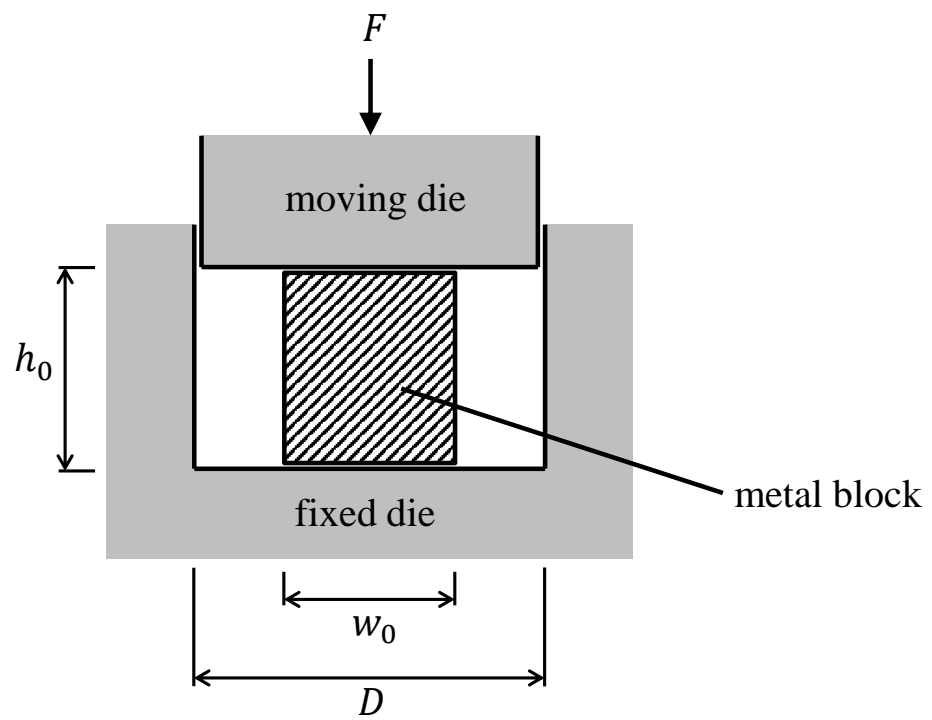


Fig. 2

**SECTION B**

4 (a) Describe the factors that determine the hardness of plain-carbon steels. Give examples to support your answers. [5]

(b) Figure 3 shows sketches of the microstructure of four iron-carbon alloy specimens at room temperature. Specimens (ii) and (iii) have an identical carbon content, which differs from both alloys (i) and (iv). Suggest the approximate carbon content of these steels and, giving reasons, rank the microstructures in order of decreasing hardness. State the names of the phases or microstructures labelled  $\alpha$ ,  $\alpha'$ ,  $\text{Fe}_3\text{C}$  and  $\text{Fe}_3\text{C}/\alpha$ . [8]

(c) Describe how TTT diagrams are used to map microstructure formation in plain-carbon steels. Comment on the effect of changing the transformation temperature on the microstructure and properties of plain-carbon steels. Hence, explain the formation of microstructures (ii) and (iii) sketched in Fig. 3. [8]

(d) With reference to their properties, explain which of the microstructures in Fig. 3 are suitable for the manufacture of railway tracks. [4]

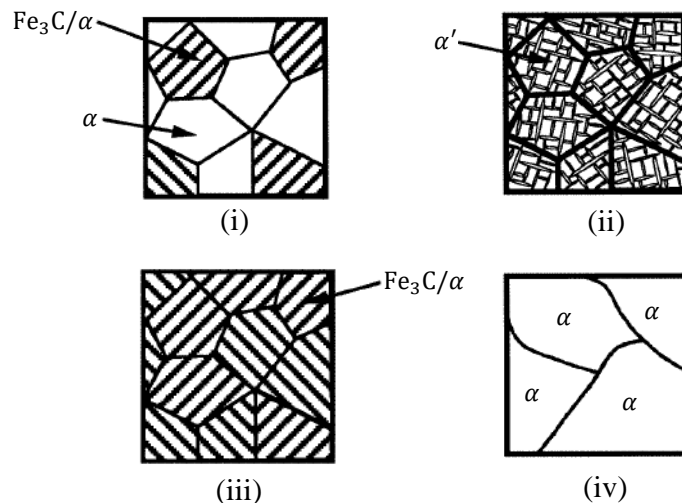


Fig. 3

- 5 (a) With reference to an aluminium-copper alloy, explain the parameters that affect the rate of diffusion of copper within aluminium. [6]
- (b) Explain how diffusion can be used to:
- (i) optimise the properties of heat treatable Al alloys; [4]
  - (ii) dope semiconductors. [3]
- (c) Boron is to be diffused into the surface of a silicon wafer. We can approximate the wafer to be an infinitely thick plate with boron maintained at a concentration  $C_0$  at  $x = 0$ . Assuming one-dimensional diffusion of boron over a region  $x \geq 0$  :
- (i) Write the governing differential equation for the diffusion of boron into silicon, and explain its physical basis. [3]
  - (ii) Sketch the time-dependent variation in the concentration of boron in the silicon wafer, indicating the appropriate boundary conditions. Hence, write an expression for the variation of the concentration  $C$  of boron as a function of distance  $x$  into the wafer and time  $t$ . [3]
  - (iii) Assuming that the activation energy for the diffusion of boron into silicon is  $300 \text{ kJ mol}^{-1}$ , estimate the ratio between the diffusion times needed to achieve the same penetration depth of boron into silicon at  $1000 \text{ }^\circ\text{C}$  and  $1200 \text{ }^\circ\text{C}$  . [6]

6 (a) Distinguish between diffusional creep and power-law creep in a metallic alloy. [6]

(b) Briefly explain the mechanisms via which alloys achieve creep resistance. Give an example where creep resistant alloys are used. [6]

(c) A metallic alloy deforms in uniaxial tension by power-law creep with a creep exponent  $n$  according to the relationship

$$\dot{\epsilon} = \dot{\epsilon}_0 \left( \frac{\sigma}{\sigma_0} \right)^n$$

where  $\dot{\epsilon}$  is the true strain rate at a true stress  $\sigma$ , and  $\dot{\epsilon}_0$  and  $\sigma_0$  are material constants. The creep deformation of the alloy occurs in an incompressible manner. A rod with initial cross-sectional area  $A_0$  and length  $L_0$  is unloaded for time  $t < 0$  and subjected to a constant tensile load  $W$  for time  $t \geq 0$ . You may assume that the above power-law creep relationship holds throughout the deformation, i.e. from the onset of loading up to rupture.

(i) Derive an expression for the initial true strain rate  $\dot{\epsilon}_{ss}$  of the rod at time  $t = 0$ . [3]

(ii) Derive an expression for the rupture time  $t_f$ , defined as the time for the cross-sectional area of the rod to reduce to zero, in terms of  $\dot{\epsilon}_{ss}$  and  $n$ . You may neglect necking in your analysis. [6]

(iii) Giving reasons, explain whether you expect your answer to part (c)(ii) to be an upper or lower bound to the actual rupture time. [4]

**END OF PAPER**