Loughborough University

ADVANCED PRINCIPLES OF MATERIALS
(24MPC111)

Semester 1 2024/25 In-Person Exam paper

This examination is to take place in-person at a central University venue under exam conditions. The standard length of time for this paper is **2 hours**.

You will not be able to leave the exam hall for the first 30 or final 15 minutes of your exam. Your invigilator will collect your exam paper when you have finished.

Help during the exam

Invigilators are not able to answer queries about the content of your exam paper. Instead, please make a note of your query in your answer script to be considered during the marking process. If you feel unwell, please raise your hand so that an invigilator can assist you.

You may use a calculator for this exam. It must comply with the University's Calculator Policy for In-Person exams, in particular that it must not be able to transmit or receive information (e.g. mobile devices and smart watches are **not** allowed).

Answer ALL questions.

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1. For the following dislocation reaction:

$$\mathbf{b}_1 + \frac{a}{6}[\bar{2}\bar{1}\bar{1}] + \frac{a}{3}[\bar{1}11] \rightarrow \frac{a}{2}[\bar{1}10]$$

(a) Determine the Burgers vector of the dislocation labelled $\mathbf{b}_1$. [2 marks]

(b) Briefly explain what the dislocation reaction depicts. [3 marks]

(c) Show whether the reaction results in a decrease or increase in energy. [2 marks]

(d) What plane does the dislocation reaction happen in? [3 marks]

(e) Briefly describe how the dislocation with the Burgers vector $\frac{a}{3}[\bar{1}11]$ could form and how the FCC stacking sequence is affected by the dislocation. [4 marks]

(f) Determine the equilibrium spacing of the Shockley partials in FCC Cu. At their equilibrium spacing, the forces on the Shockley partials - given by equation (Equation 1) - are balanced. [6 marks]

Equations and data for question 1:

$$f_{edge} + f_{screw} + f_{SF} = 0 \qquad \text{(Equation 1)}$$

f_{edge} and f_{screw} are the repulsive forces per unit length due to the edge and screw components of the (mixed) partial dislocation.

$$f_{edge} = \left(\frac{Gb^2}{8\pi(1-\nu)} \cdot \frac{1}{r}\right) \qquad \text{(Equation 2)}$$

$$f_{screw} = -\left(\frac{Gb^2}{24\pi} \cdot \frac{1}{r}\right) \qquad \text{(Equation 3)}$$

f_{SF} is the repulsive force per unit length due to the stacking fault energy $= -\gamma_{SF}$.

Data for Cu:

The shear modulus G is 46 GPa, the lattice parameter = 3.614 91 Å, the Poisson's ratio $\nu = 0.340$ and the stacking fault energy $\gamma_{SF} = 45\,\text{mJ}\,\text{m}^{-2}$.

b is the magnitude of the Burgers vector of the perfect dislocation and r is the spacing of the Shockley partials.

continued...

2. (a) A long steel bar is plated at one end with a 15 µm layer of pure Ni. The bar is then heat-treated at 1100 °C for 1 h.

   (i) Calculate the Ni concentration at a distance x of 10 µm beneath the original layer. [7 marks]

   (ii) How thick does the Ni layer need to be to achieve a concentration of 15 atomic% Ni at 10 µm beneath the original layer? The heat treatment time and temperature cannot be changed. [5 marks]

   (b) Given that Ni and Fe have a similar atomic radius, give a brief explanation of the likely mechanism of diffusion of Ni in Fe. [3 marks]

   (c) The steel also contains C. Given that C is a much smaller atom than Fe, give a brief explanation of the likely mechanism of diffusion of C in Fe. [3 marks]

   (d) Briefly explain whether the C atoms or Ni atoms are likely to migrate faster. [2 marks]

Equations and data for question 2:

Diffusion data for Ni diffusing in Fe:

$D_0 = 0.77\,\text{cm}^2\,\text{s}^{-1}$ and $Q = 2.905\,\text{eV}$

$R = 8.314\,\text{J mol}^{-1}\,\text{K}^{-1}$

$1\,\text{eV} = 1.602\,18\times10^{-19}\,\text{J}$

Avogadro's number $= 6.022\times10^{23}\,\text{mol}^{-1}$

You may use one or more of the following equations:

$$C(x,t) = \frac{B}{(\pi Dt)^{0.5}} \exp\left(-\frac{x^2}{4Dt}\right) \qquad \text{(Equation 4)}$$

$$C(x,t) = C_s - (C_s - C_0)\text{erf}\left(\frac{x}{2(Dt)^{0.5}}\right) \qquad \text{(Equation 5)}$$

$$C(x,t) = \frac{C_1 + C_2}{2} - \frac{C_1 - C_2}{2}\text{erf}\left(\frac{x}{2(Dt)^{0.5}}\right) \qquad \text{(Equation 6)}$$

An error function table is provided in Table Q2 on page 6.

continued...

3. (a) A powerplant component is required to operate at a shear-stress σ of 100 MPa and a homologous temperature of 0.50. It must operate for 18 years and the shear strain in the component cannot exceed 0.20. The component is specified to be produced using 316 stainless steel with a grain size of 200 µm.

   (i) Use Figure Q3, show whether or not the component could operate under the service conditions for the required time. [12 marks]

   (ii) Briefly, comment on the results and suggest what could be done to improve the service life with the same operating conditions. [2 marks]

   (b) Deformation mechanism maps often include the ideal / theoretical shear strength. Briefly explain what is meant by the ideal shear strength and why this is rarely observed in FCC metals. [2 marks]

   (c) The deformation map in Figure Q3 gives two separate regions for diffusional flow. Explain what may influence the position of the boundary between the two regions. [4 marks]

Equations and data for question 3:

The general form of the creep equation for the shear strain rate $\dot{\gamma}$:

$$\dot{\gamma} = A\left(\frac{D_{eff}Gb}{kT}\right)\left(\frac{b}{d}\right)^{p}\left(\frac{\sigma}{G}\right)^{n} \qquad \text{(Equation 7)}$$

316 stainless steel is fully austenitic (face centred cubic).

The alloy melting temperature is 1537 °C.

The alloy shear modulus is 80 GPa.

Lattice diffusion data: $D_{0L} = 3.7\times10^{-5}\,\text{m}^2\,\text{s}^{-1}$ and $Q_l = 280\,\text{kJ mol}^{-1}$.

Boundary diffusion data: $\delta D_{0b} = 2.0\times10^{-13}\,\text{m}^3\,\text{s}^{-1}$ and $Q_b = 167\,\text{kJ mol}^{-1}$.

Take $\delta = b$.

The lattice parameter $a = 3.649$ Å.

The Boltzmann constant $k = 1.381\times10^{-23}\,\text{J K}^{-1}$.

In the diffusional creep region, $A = 42$.

In the power-law creep region, $A = 8.10\times10^{11}$ and $n = 7.0$. You may assume that lattice diffusion dominates in the whole of the power-law creep region.

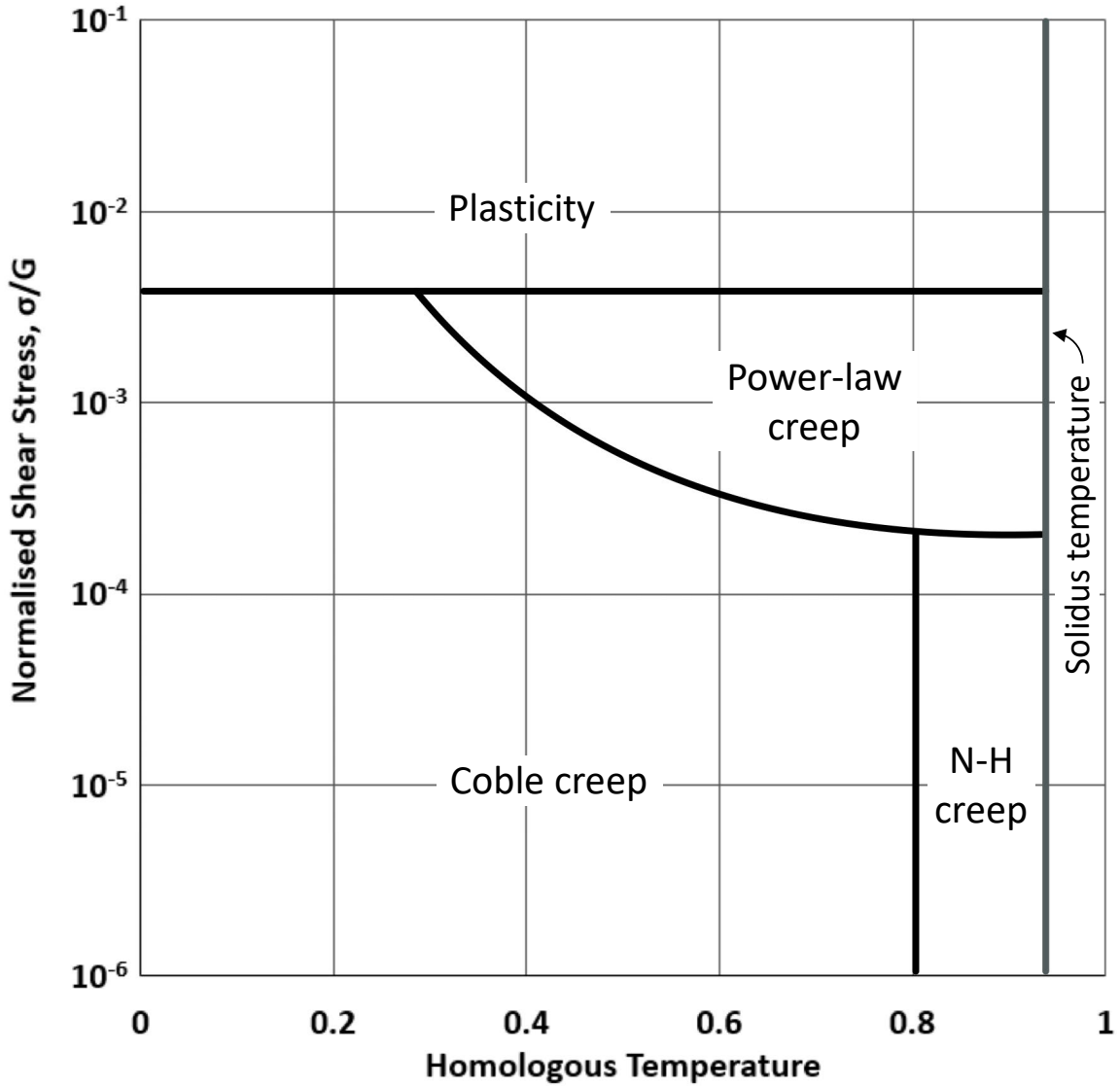

Figure Q3: Deformation mechanism map for 316 stainless steel with a grain size of 200 µm.

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x	0	1	2	3	4	5	6	7	8	9
0.0	0.0000	0.0113	0.0226	0.0338	0.0451	0.0564	0.0676	0.0789	0.0901	0.1013
0.1	0.1125	0.1236	0.1348	0.1459	0.1569	0.1680	0.1790	0.1900	0.2009	0.2118
0.2	0.2227	0.2335	0.2443	0.2550	0.2657	0.2763	0.2869	0.2974	0.3079	0.3183
0.3	0.3286	0.3389	0.3491	0.3593	0.3694	0.3794	0.3893	0.3992	0.4090	0.4187
0.4	0.4284	0.4380	0.4475	0.4569	0.4662	0.4755	0.4847	0.4937	0.5027	0.5117
0.5	0.5205	0.5292	0.5379	0.5465	0.5549	0.5633	0.5716	0.5798	0.5879	0.5959
0.6	0.6039	0.6117	0.6194	0.6270	0.6346	0.6420	0.6494	0.6566	0.6638	0.6708
0.7	0.6778	0.6847	0.6914	0.6981	0.7047	0.7112	0.7175	0.7238	0.7300	0.7361
0.8	0.7421	0.7480	0.7538	0.7595	0.7651	0.7707	0.7761	0.7814	0.7867	0.7918
0.9	0.7969	0.8019	0.8068	0.8116	0.8163	0.8209	0.8254	0.8299	0.8342	0.8385
1	0.8427	0.8468	0.8508	0.8548	0.8586	0.8624	0.8661	0.8698	0.8733	0.8768
1.1	0.8802	0.8835	0.8868	0.8900	0.8931	0.8961	0.8991	0.9020	0.9048	0.9076
1.2	0.9103	0.9130	0.9155	0.9181	0.9205	0.9229	0.9252	0.9275	0.9297	0.9319
1.3	0.9340	0.9361	0.9381	0.9400	0.9419	0.9438	0.9456	0.9473	0.9490	0.9507
1.4	0.9523	0.9539	0.9554	0.9569	0.9583	0.9597	0.9611	0.9624	0.9637	0.9649
1.5	0.9661	0.9673	0.9684	0.9695	0.9706	0.9716	0.9726	0.9736	0.9745	0.9755

Table Q2.

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