ADVANCED PRINCIPLES OF MATERIALS
(23MPC111)

Semester 1 2023/24 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 THREE questions.

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1. (a) Using the concept of disregistry and the Peierls stress, explain how the width of a dislocation is defined. [4]

   (b) Calculate the Peierls stress τ_p for a $\frac{a}{6}\langle 112\rangle$ Shockley partial in FCC Ag. Give your answer in MPa. [6]

   (c) How you would expect your result for the Peierls stress to compare to the theoretical strength of a crystal? State why any differences arise. [4]

   (d) The following dislocation reaction depicts a perfect dislocation in an FCC crystal structure dissociating into two Shockley partials:

$$\frac{a}{2}[\bar{1}01] \rightarrow \frac{a}{6}[\bar{2}\bar{1}1] + \frac{a}{6}[\bar{1}12]$$

   Determine the plane that the reaction takes place in and show whether there is a net increase or decrease in the energy due to reaction. [4]

   (e) The following dislocation reaction in an FCC crystal structure depicts the unfaulting of a sessile Frank loop lying in a (111) plane by two Shockley partials.

$$\frac{a}{6}[\bar{1}2\bar{1}] + \frac{a}{6}[2\bar{1}\bar{1}] + \frac{a}{3}[111] \rightarrow \frac{a}{2}[110]$$

   Explain whether the resultant dislocation is sessile or glissile. Show all working. [2]

Data and equations for question 1:

$$\tau_p = \frac{2G}{1-\nu}\exp\left(\frac{-2\pi w}{b}\right) \qquad \text{(Equation 1)}$$

where w is the dislocation width, d is the interplanar spacing and b is the Burgers vector. $G = 27.8\,\text{GPa}$, the Poisson's ratio $\nu = 0.333$, $w = d/(1-\nu)$ and $a = 4.0853\,\text{Å}$.

Take the interplanar spacing to be that of the $\{111\}$ planes.

$$d_{hkl} = \frac{a}{\sqrt{h^2+k^2+l^2}} \qquad \text{(Equation 2)}$$

2. (a) Diffusion is a random phenomenon at the atomic level. Despite this, a preferred diffusion direction is typically observed - usually from regions of higher concentration to that of lower concentration. Explain briefly why this is the case. [2]

   (b) Give details of the likely diffusion mechanism for the following:

      (i) Small carbon and nitrogen atoms diffusing in steel during a carbonitriding process. [3]

      (ii) Ag atoms diffusing in an Ag-Au diffusion couple during a heat-treatment. Ag and Au atoms are similar in size. Assume that the vacancy concentration is negligible. [3]

      (iii) Diffusion of Mg and Si atoms to form Mg_2Si strengthening precipitates in an Al-Mg-Si alloy. The alloy was rapidly quenched from a high temperature where the alloy was a single solid solution. [3]

   (c) Hydrogen induced cracking in pipeline steels can occur due to a corrosion process that produces atomic hydrogen which then diffuses into the steel. To investigate the diffusion of hydrogen in steel, the inside of a steel pipe with a wall thickness of 3 mm was exposed to hydrogen at a constant pressure of 0.1 MPa.

      (i) Calculate the steady-state flux of hydrogen at 100 °C through the pipe wall. Assume the hydrogen concentration drops to zero outside the pipe. The concentration of hydrogen at the inside wall of the pipe can be determined from the pressure using:

$$C = k \cdot P^{0.5} \qquad \text{(Equation 3)}$$

      where C is the concentration, P is the pressure in MPa and k is a solubility constant $= 21.7\,\mathrm{mol\,m^{-3}\,MPa^{-0.5}}$. [7]

      (ii) Calculate the time required to diffuse 2 mol of hydrogen through the pipe wall if the inside surface area of the pipe is $1\,\mathrm{m}^2$. [2]

Data and equations for question 2:

$D_0 = 2.82\times10^{-3}\,\mathrm{cm^2\,s^{-1}}$ and $Q = 3.44\times10^{4}\,\mathrm{J\,mol^{-1}}$
$R = 8.314\,\mathrm{J\,mol^{-1}\,K^{-1}}$

$$J = -D\left(\frac{\partial C}{\partial x}\right) \qquad \text{(Equation 4)}$$

continued. . .

3. (a) Explain why in the dislocation / power law creep regime, lattice diffusion dominates at high temperatures despite dislocation core diffusion being faster at all temperatures. [3]

   (b) Provide brief details of the following mechanisms of plastic flow given in the deformation mechanism map in Figure Q3.

      (i) Plasticity. [3]

      (ii) Diffusional flow. [3]

   (c) Ni with a grain size of 1 mm is chosen for a component designed to operate at elevated temperatures. Using Figure Q3, calculate the shear strain rate $\dot{\gamma}$ if the operating conditions are an applied normalised shear stress of 1×10^{-3} at $0.4\mathrm{T}_m$. State all assumptions and show all working. [9]

   (d) The component must be able to operate continuously for one year under the conditions given in part (c) without the shear strain γ exceeding 0.1. Is the material suitable for the application? [2]

Data and equations for question 3:

$$\dot{\gamma} = A\left(\frac{D_{eff}Gb}{kT}\right)\left(\frac{b}{d}\right)^p\left(\frac{\sigma}{G}\right)^n \qquad \text{(Equation 5)}$$

Melting temperature of Ni $\mathrm{T}_m = 1726\,\mathrm{K}$

Shear modulus of Ni $G = 78.9\,\mathrm{GPa}$

Lattice diffusion data: $D_{0L} = 1.9\times10^{-4}\,\mathrm{m^2\,s^{-1}}$ and $Q_l = 284\,\mathrm{kJ\,mol^{-1}}$

Boundary diffusion data: $\delta D_{0b} = 3.5\times10^{-15}\,\mathrm{m^3\,s^{-1}}$ and $Q_b = 115\,\mathrm{kJ\,mol^{-1}}$

Dislocation core diffusion data: $a_c D_{0c} = 3.1\times10^{-23}\,\mathrm{m^4\,s^{-1}}$ and $Q_c = 170\,\mathrm{kJ\,mol^{-1}}$

$D_{eff} = D_L + D_B\dfrac{\delta}{d}$.

$D_{eff} = D_L + \rho_{ss}a_c D_c$.

Take $\delta = b$.

The steady state dislocation density $\rho_{ss} = 1.0\times10^{14}\,\mathrm{m^{-2}}$.

Burgers vector $b = 2.49\times10^{-10}\,\mathrm{m}$.

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

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

In the dislocation / powerlaw creep regime, $A = (\sqrt{3})^{n+1}B$, where $B = 3\times10^6$.

In the dislocation / powerlaw creep regime, $n = 4.6$.

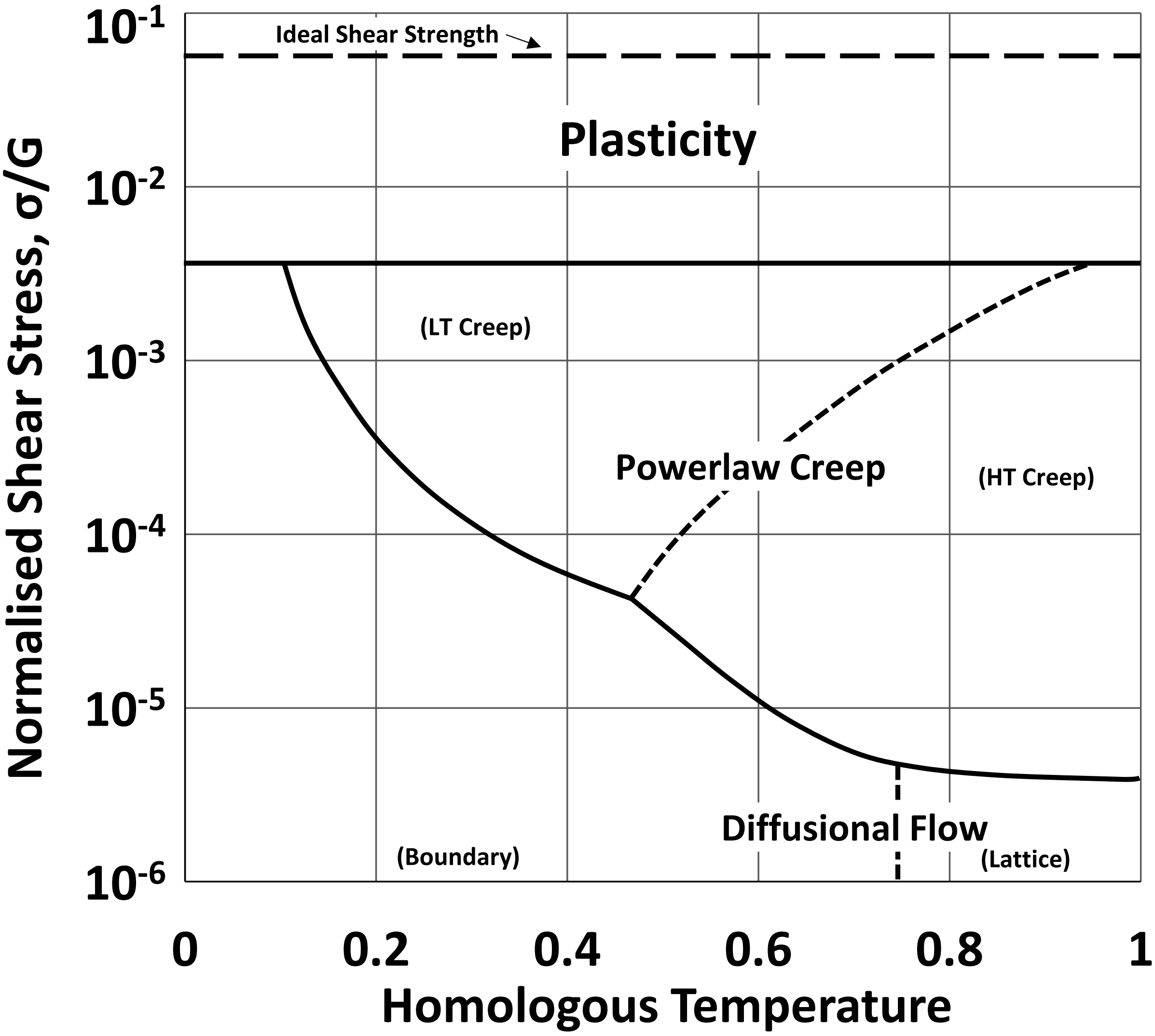

Figure Q3: Deformation mechanism map for pure nickel with a grain size of 1 mm.