Spring 2015 Ph.D. Qualifying Exam: Materials
Work All Problems

Closed Book & Closed Notes
2 Hours

1) A high strength steel has a yield strength (Y.S.) of 1.5 GPa. Assuming plain strain conditions,

(a) Compute the fracture toughness (K_{IC}) for a sharp through thickness crack (see Figure 1(a)) with a half crack length of a = 2 mm, and an applied stress of 700 MPa.
(b) Compute the fracture toughness (K_{IC}) for a penny crack (see Figure 1 (b)) with a half crack length of a = 2 mm and applied stress of 700 MPa.
(c) Discuss the difference in values computed in parts (a) and (b).

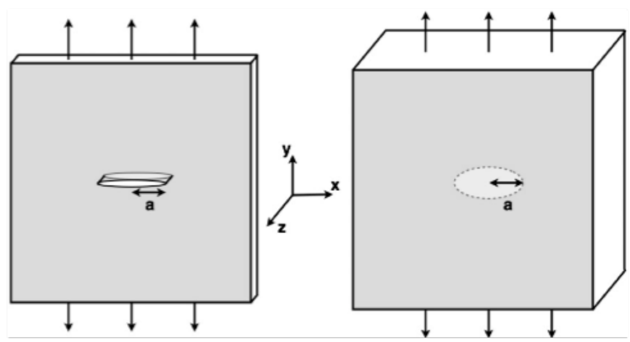

Figure 1(a) Figure 1(b)

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2) Graphene is a two dimensional material made of carbon atoms (see Figure 2), and has a thickness of ~0.335 nm (one atom thick sheet of carbon atoms). Assuming that linear elastic fracture mechanics can be used, (a) discuss the approach to compute the fracture toughness of the graphene sheet, (b) what are the boundary conditions for this problem and how will they differ from Question 1?

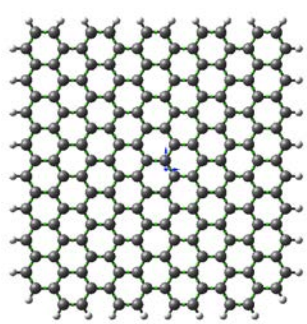

Figure 2

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3) Consider a cylindrical pipe containing hydrogen gas. You are to design a membrane that separates a high concentration region from a low concentration region. The high-concentration region maintains a constant hydrogen concentration of 5.70×10^6 atoms/cm^3, and the low-concentration region maintains a concentration of 1.0×10^4 atoms/cm^3. What is the minimum membrane thickness that limits the transfer of hydrogen atoms to 10^6 atoms/hour at T = 300 K? Assume the hydrogen diffusion activation energy is 3600 cal/mol, and the pre-exponential constant is 0.0012 cm^2/s in the membrane.

(Use R = 1.987 cal/K-mole)

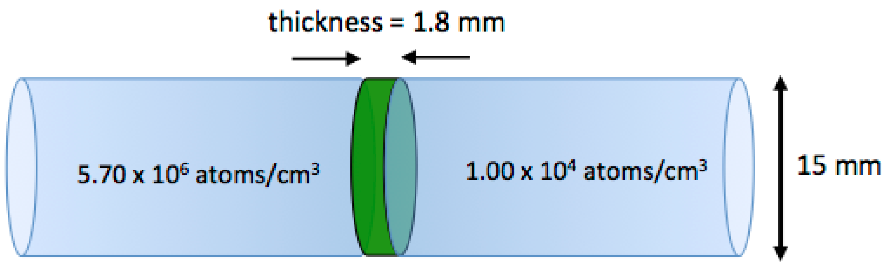

Figure 3

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4) 3-D Printing has gained popularity with the aerospace industry for making metal parts. One of the metal printing methods is selective laser sintering (SLS), which uses a laser beam to scan a metal powder bed layer by layer as shown in Figure 4. The metal powder particles are joined together by sintering. Sintering occurs by diffusion of atoms through the microstructure.

(a) What is the driving force for diffusion? What are the influencing factors for the driving force?
(b) What are some of the common sintering mechanisms? (Hint: think about the different paths the atoms take to get from one spot to another)
(c) Figure 5 shows an Arrhenius plot for some metals and ceramics. Assume the metal powder used for the SLS process is iron with a BCC structure. Read Figure 5 and calculate the required activation energy (the gas constant R = 8.314 J/mol).
(d) Assume the molecular weight of iron is 56 g/mol, and its density is 7.87 g/cm^3, average powder particle diameter is 100μm, the laser power is 200W, and the energy absorption rate for the iron powder is 5%, estimate the maximum scanning speed such that the iron powder can be sintered (hint: use the activation energy obtained).
(e) Assume the heating and cooling of the powders are on the same time scale, according to your previous calculation, what microstructure is most likely to be formed after the laser scan and how would that affect the strength of the part made from this process?

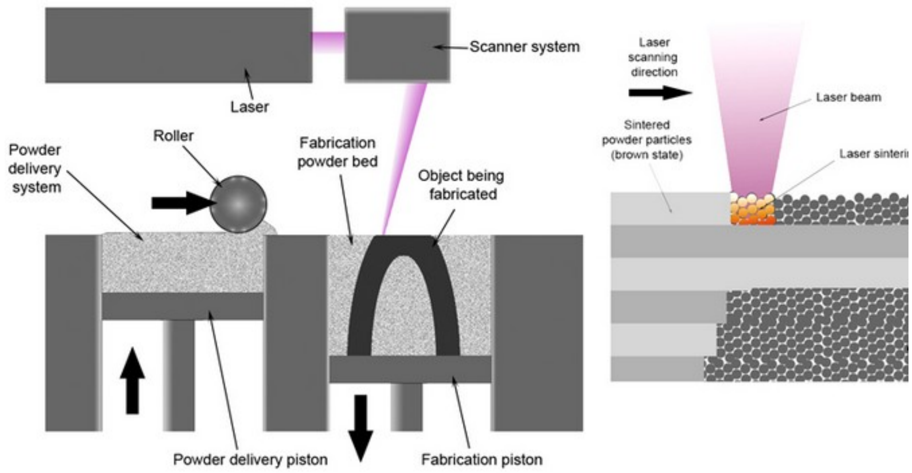

Figure 4. Illustration of beam deposition process.

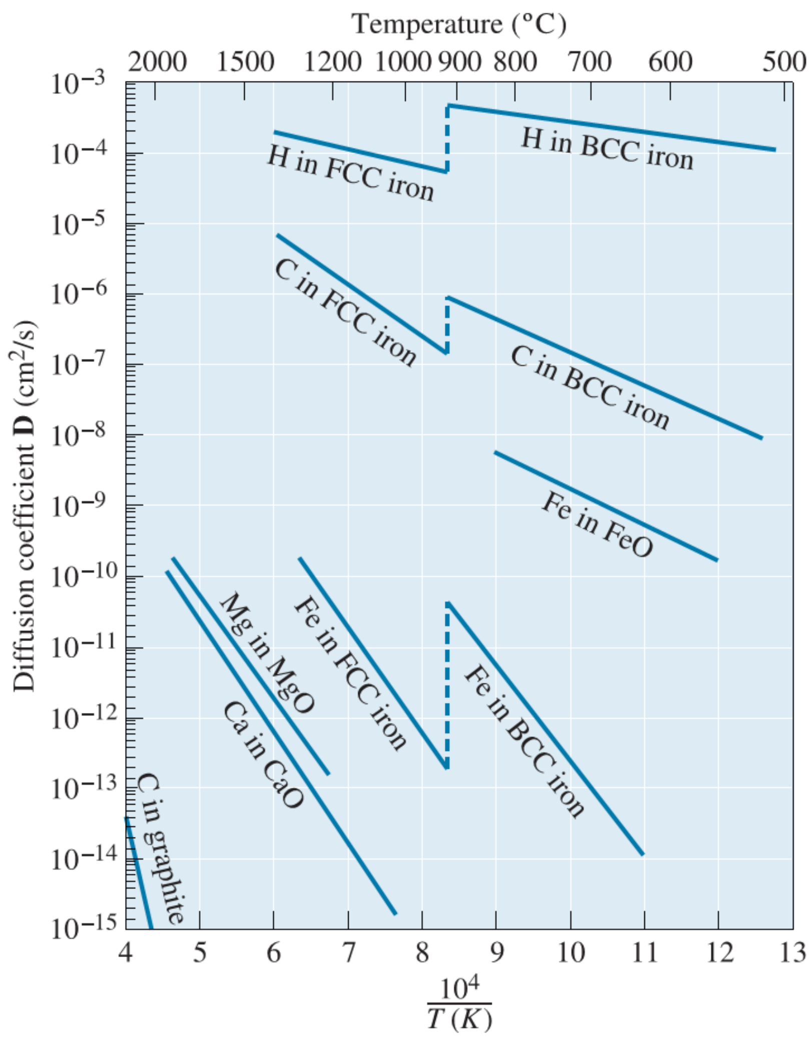

Figure 5. The diffusion coefficient D as a function of reciprocal temperature.

5) The sliver-copper binary phase diagram is provided below.

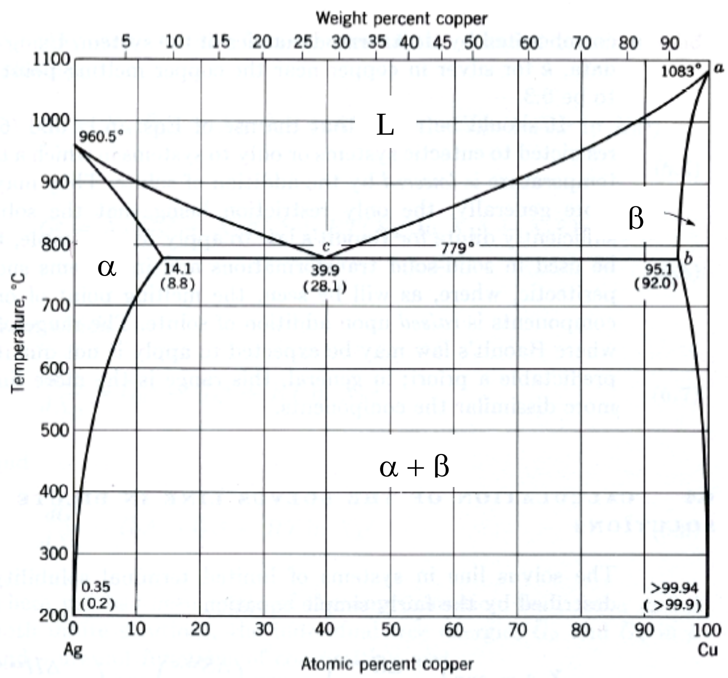

Figure 6. Phase diagram for Ag-Cu.

(a) Write down the name of the 3-phase reaction and the composition of each phase involved.

(b) What is the maximum solubility of copper in silver?

(c) Consider a 60 wt% Cu – 40 wt% Ag alloy. During an equilibrium cooling process from 1000 ^{o}C, determine:

(i) The liquidus temperature.
(ii) The composition of the first solid phase to form.
(iii) The composition of each phase at a temperature of 700 ^{o}C.
(iv) The amount of each phase at a temperature of 700 ^{o}C.

Spring 2016 Ph.D. Qualifying Exam: Materials
Work All Problems

Closed Book & Closed Notes
2 Hours

1. (20 pts) A high strength steel has a yield strength (Y.S.) of 1.5 GPa. Assuming plain strain conditions,
   (a) Compute the fracture toughness (K_{IC}) for a sharp crack (see Figure 1 (a)) or a through thickness crack with a half crack length of *a*= 2 mm, and an applied stress of 700 MPa.
   (b) Compute the fracture toughness (K_{IC}) for a penny crack (see Figure 1 (b)) with a half crack length of *a*= 2 mm and applied stress of 700 MPa.
   (c) Discuss the difference in values computed in parts (a) and (b).
   (d) If plain stress conditions are used, will K_{IC} values computed in parts (a) & (b) change? Discuss the difference.

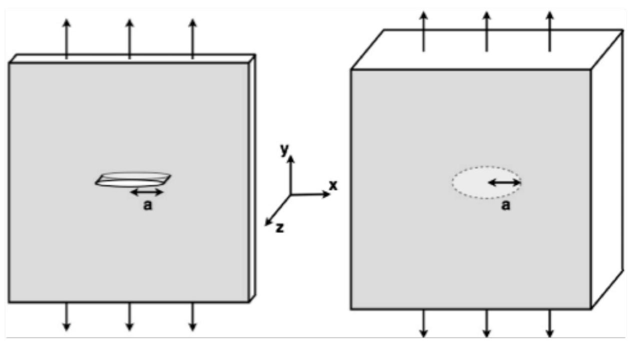

Figure 1(a) Figure 1(b)

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2. (a) (5 pts) Gaseous hydrogen at a constant pressure of 1.013 MPa (10 atm) is to flow within the inside of a thin-walled cylindrical tube of nickel that has a radius of 0.1 m. The temperature of the tube is to be 300ºC and the pressure of hydrogen outside of the tube will be maintained at 0.01013 MPa (0.1 atm). Calculate the minimum wall thickness if the diffusion flux is to be no greater than 1×10^{-7} mol/m$^2\cdot$s.

   The concentration of hydrogen in the nickel, C_H (in moles hydrogen per m^3 of Ni), is a function of hydrogen pressure, P_H (in MPa), and absolute temperature (T) according to

$$C_H = 30.8\sqrt{P_H}\,\exp(-\frac{12.3\ kJ/mol}{RT})$$

   Furthermore, the diffusion coefficient D_H for the diffusion of H in Ni is dependent on temperature and can be calculated as:

$$D_H = 4.76 \times 10^{-7} \exp(-\frac{39.56\ kJ/mol}{RT})$$

where R = 8.31 J/mol-K.

(b) (5 pts) For thin-walled cylindrical tubes that are pressurized, the circumferential stress is a function of the pressure difference across the wall (ΔP), cylinder radius (r), and tube thickness (Δx) as:

$$\sigma = \frac{r\Delta P}{4\Delta x}$$

Calculate the circumferential stress to which the wall of this pressurized cylinder is exposed.

(c) (5 pts) The room-temperature yield strength σ_y of Ni is 100 MPa and, furthermore, σ_y diminishes about 5 MPa for every 50ºC increase in temperature. Would you expect the wall thickness computed in part (a) to be suitable for this Ni cylinder at 300ºC? Why or why not?

(d) (5 pts) If this thickness is found to be suitable, determine the minimum thickness that could be used without exceeding the yield strength of the tube walls. How much would the diffusion flux increase with this reduction in thickness? On the other hand, if the thickness determined in part (c) is found to be unsuitable, then specify a minimum thickness that you would use. In this case, how much of a diminishment in diffusion flux would result? (Hint: you may assume a safety factor of 2.0).

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3. The objective of this problem is to test fundamentals of materials and ability of analytical thinking. Clear and well discussed (to the point) solution in technical language will carry full marks.

(a) (4 pts) Hall-Petch equation – The relationship between _______ strength and ______ size in a ________ material, that is ________________, where $\sigma_y = \sigma_o + Kd^{-1/2}$, where σ_y is ______, σ_o is _______, and d is _______.

(b) (4 pts) Show a typical plot for Hall-Petch equation for typical sintered metals with grain size in microcrystalline regime.

(c) (4 pts) Discuss reasons for validity or invalidation of Hall-Petch equation for typical sintered metals with grain size in nanometers scale regime (<10 nm).

(d) (4 pts) Show a typical plot for Hall-Petch equation for nanometer scale typical metals (<10 nm).

(e) (4 pts) List one experimental technique used for visualization of metal nanostructured grains and grain boundaries. Elaborate in few lines fundamental operating principle of this technique.

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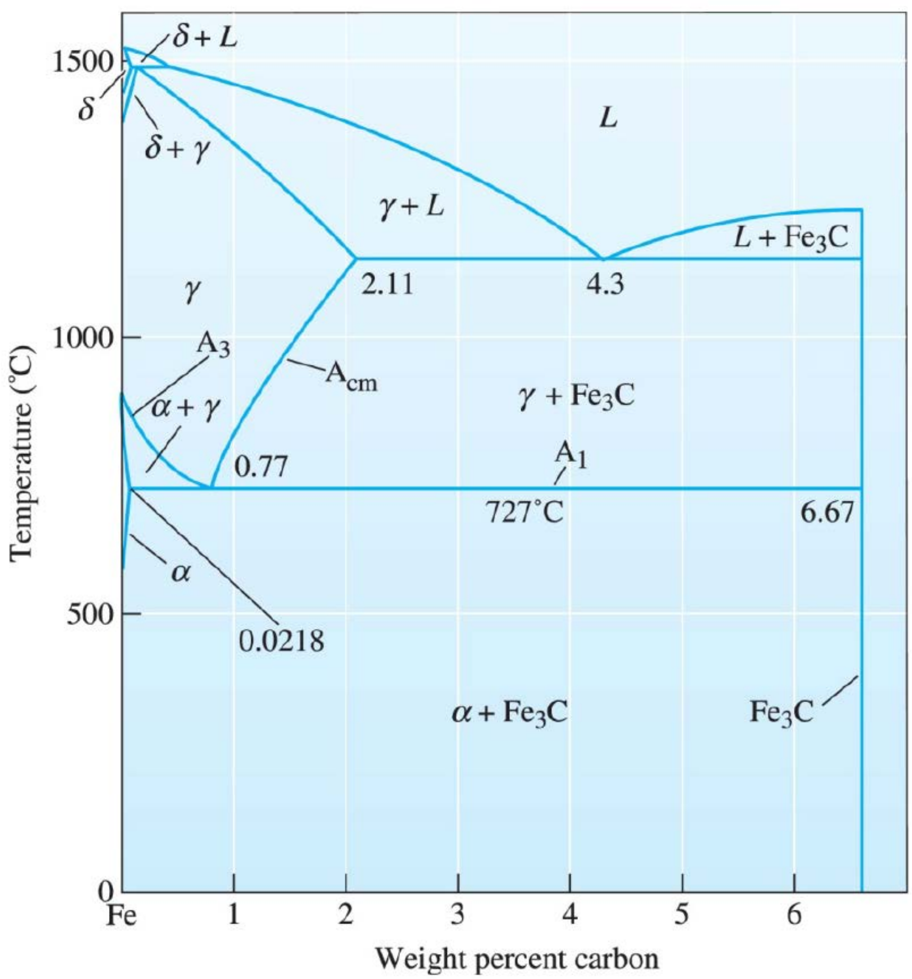
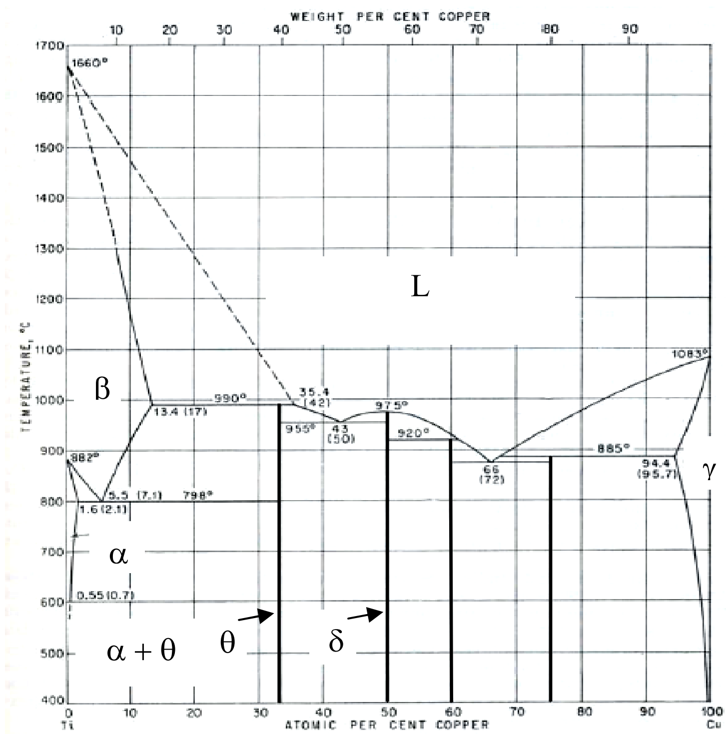
4. (20 pts) Use the below Fe-C phase diagram to answer the following questions.
   (a) Identify the composition and temperature for both the eutectic and eutectoid reactions.
   (b) At 726ºC, what microconstituents exits for a 2.0 wt.% C steel?
   (c) For the conditions in part (b), what are the amounts (in %) of each microconstituent?



5. (20 pts) The flexural strength of a composite material reinforced with glass fibers is 45,000 psi, and the flexural modulus is 18×10^6 psi. A sample, which is 0.5 in. wide, 0.375 in. high, and 8 in. long, is supported between two rods 5 in. apart. Determine the force required to fracture the material and the deflection of the sample at fracture, assuming that no plastic deformation occurs.

Sample Ph.D. Qualifying Exam in Materials
Work All Problems

(1) The titanium-copper binary phase diagram is provided below.



(a) Describe the differences between the α and θ phases of this alloy. Which phase do you expect to be more ductile?

(b) Identify the <u>eutectoid</u> reaction. Write the equation of this reaction and the composition of each phase involved.

(c) A titanium-copper alloy with 10 at.%Cu is cooled slowly from 1000 °C to room temperature; what are the composition and amounts of each phase at room temperature?

(d) If this alloy is cooled in equilibrium, draw a picture of the alloy microstructure at 850 °C.

(e) If this alloy is cooled in equilibrium, draw a picture of the alloy microstructure at room temperature.

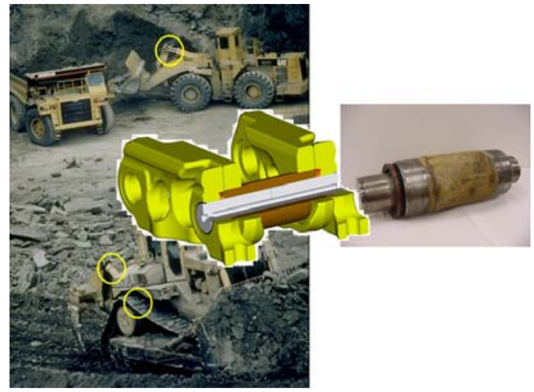
(2) The stress-strain relationship during plastic deformation of Cu is described by the equation $\sigma=310\varepsilon^{0.5}$ and for steel it is $\sigma=450\varepsilon^{0.3}$. Stress is expressed in MPa.

(a) Explain the significance of the exponent in the above relationships. In which material will strain-hardening be more effective? Explain.

(b) Calculate the energy required to deform a block of these materials that is 10 cm x 10 cm in cross-section and 100 cm long while applying a force in the axial direction.

(c) Calculate the force capacity of a machine that will be needed to plastically deform blocks of each material.

(3) Earth movers manufactured by Caterpillar, Komatzu and others use various joints when assembling these systems. One key joint is a pin-joint. This equipment operates in harsh environment, including heavy impacts, wear and friction, temperature variations (from Siberia and Alaska to middle-east and African continent). Durability of pin-joints is vital not only for efficient operation, but also for saving energy by reducing friction and wear losses as well as reducing down time, when catastrophic or gradual failure occurs.

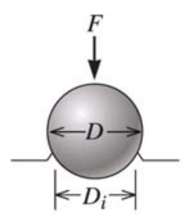


(a) Discuss materials used in the pin joint. What materials/properties are desired for the pin bulk, the pin surface and the spacing between mating surfaces in the joint. When discussing materials and related fabrication processes, identify why certain material is used, how it will be processed, what properties are desired to enable this application.

(b) One of the key properties for the application above is hardness of the material. Discuss two different techniques (not including the one discussed below) for testing hardness of a material, one for macro hardness and one for micro hardness.

(c) What material is the indenter ball made of in a Brinell hardness measurement? What three key factors related to indentation process one needs to calibrate, before testing? Derive the following formula for Brinell hardness measurement. (F is the applied force)

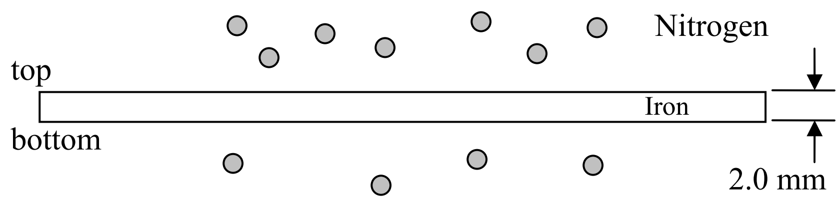
$$\text{Hardness} = \frac{F}{\frac{\pi D}{2}\left[D - \sqrt{D^2 - D_i^2}\right]}$$



Brinell test

(d) List four applications each, in addition to the above, where the macro and micro hardness techniques could be applied as a quality control process.

(4) A sheet of BCC iron 2.0 mm thick has nitrogen atmosphere on both sides at 900 ^{o}C. The system is allowed to reach steady-state equilibrium. The diffusion constant of N in BCC Fe is 0.0047 cm^2/s and the activation energy for diffusion is 18,300 cal/mol.



(a) Explain the difference between steady-state and transient diffusion. What does the composition profile of the diffusing species look like in each case?

(b) For the above example, if the diffusion flux is 1.0 * 10^{-7} kg/m^2-s and the concentration of nitrogen in the iron at the top surface is 2 kg/m^3, how far into the iron from the top surface will the concentration of nitrogen be 1.5 kg/m^3?

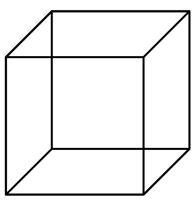
R = 1.987 cal/mol-K.

(5) Crystallography and Miller indices.

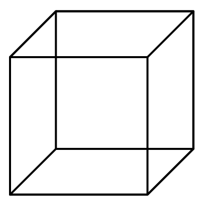
(a) Explain the concept of “slip” in metallic materials. How are Miller indices important in the definition of slip?

(b) Sketch the following directions or planes <u>within</u> the unit cell provided. Be sure to indicate your coordinate system on each cube.

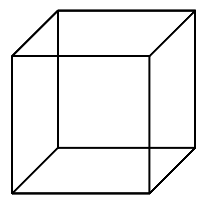
(a) [212]   (b) (101)   (c) (320)



(a)



(b)



(c)

(c) Determine the Miller indices for the shaded crystal planes in units cells A and B.