

INGE 4001 – 1er Semester - 2003 – 2004 - Section: 076  
 Instructor: O. M. Suárez – Grad student: Jacinto Yupa  
 Mid-Term Exam #2, Thursday October 16, Stéfani S-303, 5:30pm  
 Maximum time: 1 hour 30 min. - Maximum Grade: 20 pts.

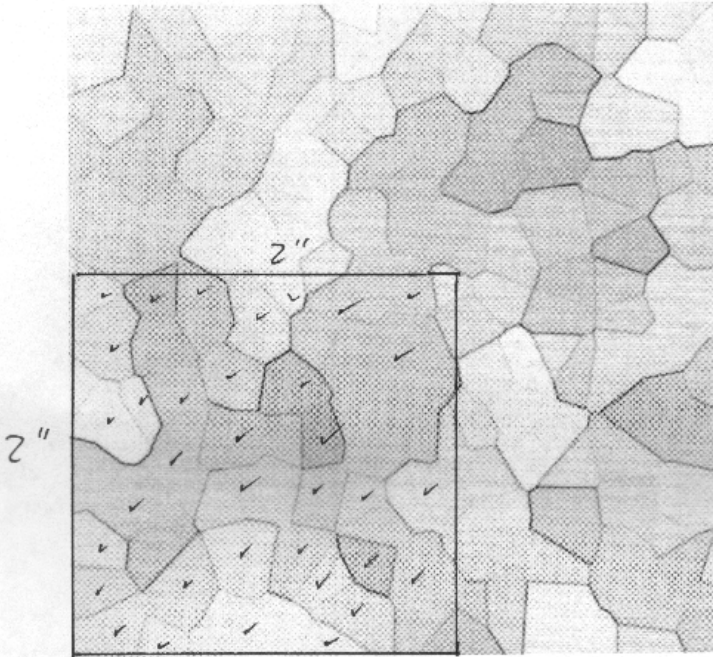
Name:

Student Number:

**Exercise N°1**

3 pts.

- a) The photograph below corresponds to a sintered electrical insulator (ceramic) etched to reveal the grain structure. Please provide its ASTM number knowing that the magnification of the image is 100x.



area = 4 in<sup>2</sup> # grains per in<sup>2</sup> =  $\frac{35}{4} = 8.75$

- b) Using the band structure, indicate the difference between an intrinsic semiconductor and an electrical insulator.  
 c) What is T<sub>C</sub> in a superconducting material?  
 d) What's called Matthiessen's rule?

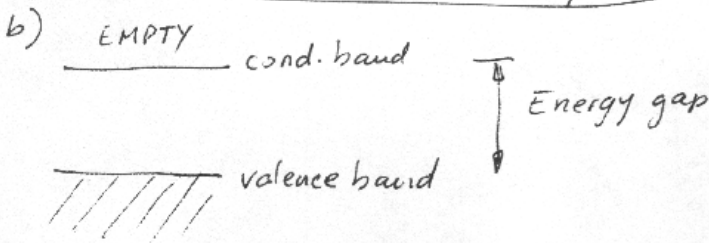
Bonus: (1 pt.)  
 Compare Fick's first law of diffusion and the equation for charge flux J across a surface. In each case, what is the driving force of flux (atoms in diffusion, charge in electrical flux)? In each case what is the "mobility" property?

a)  $N = 2^{n-1} \Rightarrow \log N = (n-1) \log 2$

$\frac{\log N}{\log 2} + 1 = n$

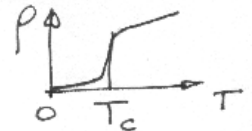
$\frac{\log 8.75}{\log 2} + 1 = 4.1$

$\Rightarrow n \approx 4$  (integer)



For intrinsic semiconductor this empty gap is relatively small  $\rightarrow$  0.5 to 2 eV. For electrical insulator, this gap is large:  $> 5$  eV

- c) T<sub>C</sub> is the temperature at which the material becomes superconductor, that means that it loses all its residual resistivity



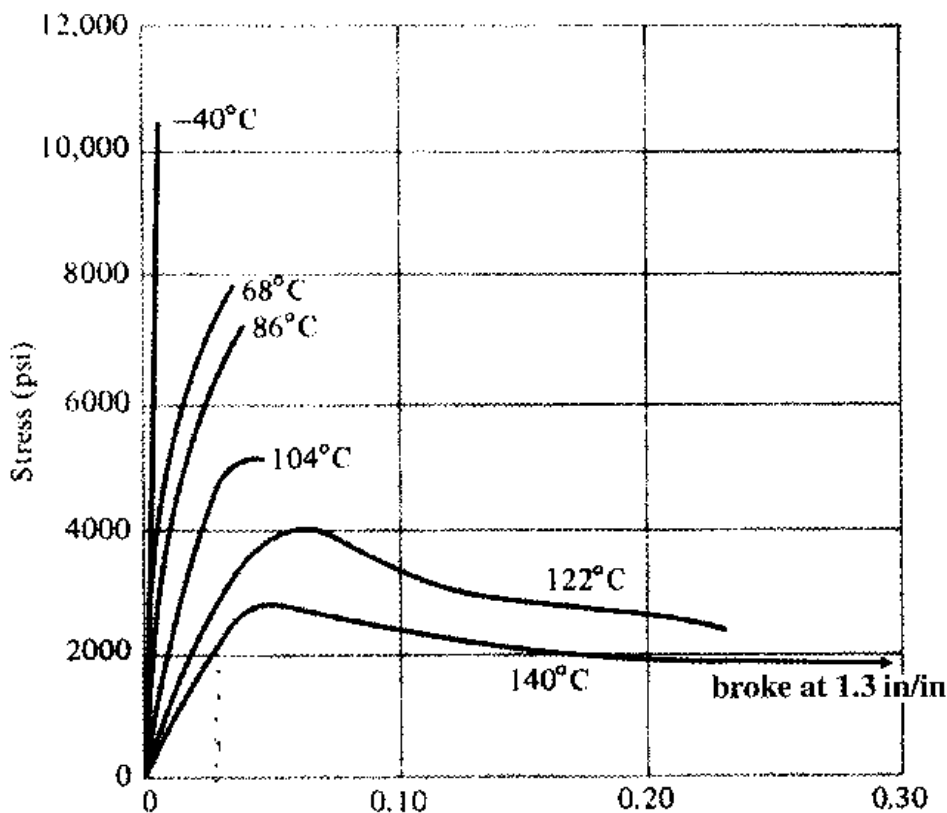
- d) Matthiessen's rule establish the additivity nature of resistivity in metals and alloys:

$\rho_{Total} = \rho_{residual} + \rho_{temperature} + \rho_{impurities} + \rho_{deformation}$

- e)  $J_{Diff.} = -D \frac{dc}{dx}$  diffusivity measures mobility of solute atoms  
 $J_{elec.} = -\mu \bar{E}$  In diffusion the driving force is the composition gradient and in charge flux, the electrical field. (measured in V/m)  
 charge mobility

**Exercise N°2**

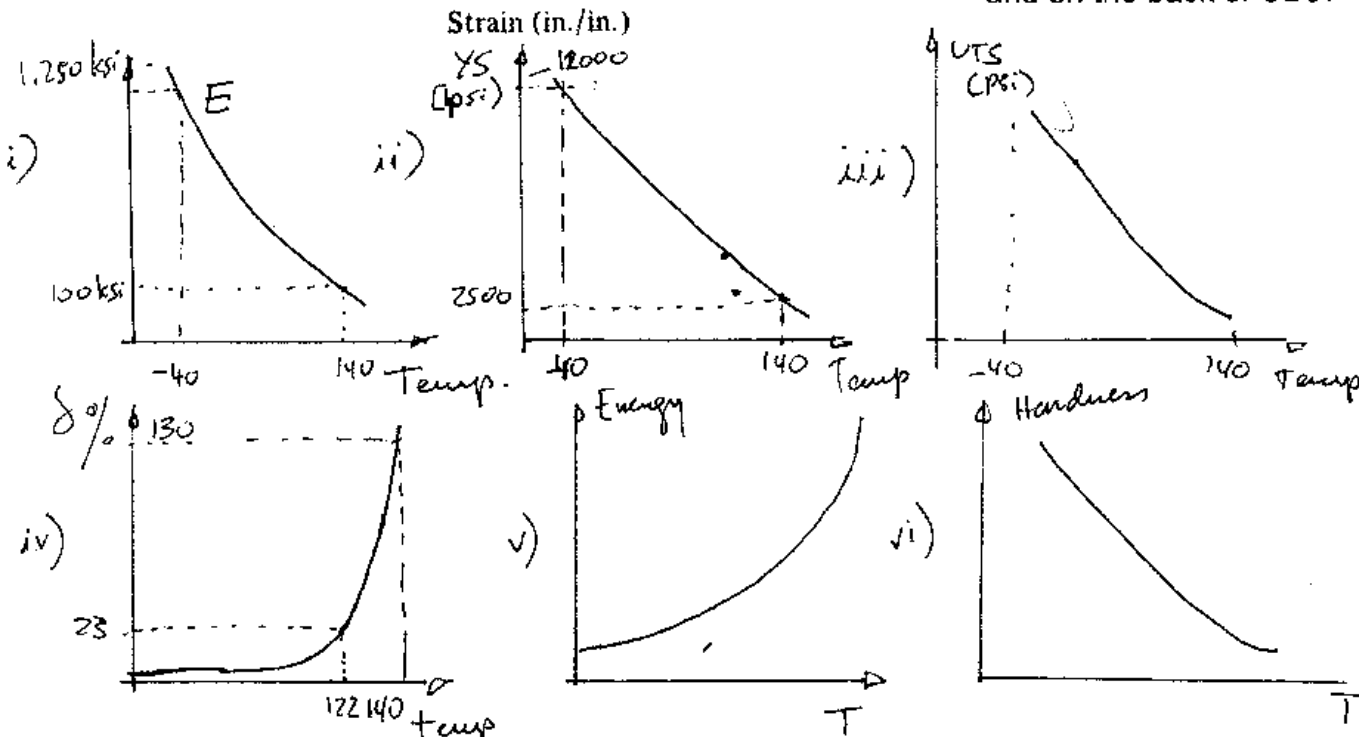
6 pts.



Polymethylmethacrylate or PMMA is a polymer used for its high transparency in reading glasses and car light covers. The plot presents tensile test results for PMMA measured at different temperatures. Please, produce another graph indicating how the following mechanical properties vary as a function of temperature (do not measure the exact quantities but make sure the graphs are more or less at scale):

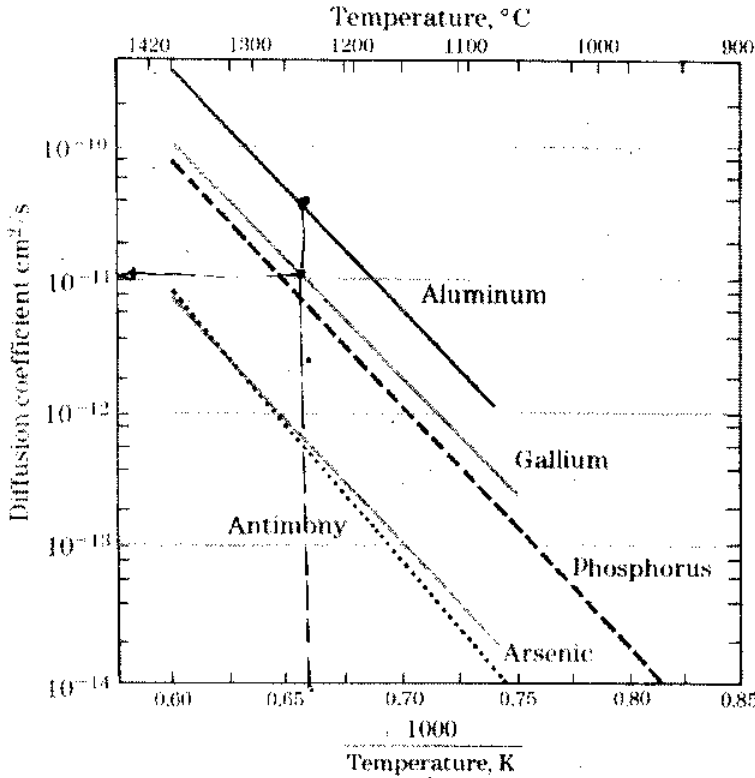
- i. Elastic modulus
- ii. Approximate yield strength
- iii. UTS
- iv. Ductility
- v. Absorbed energy to fracture.
- vi. Hardness (qualitatively)

Based on those results why do you think this material is used in glasses and on the back of CDs?



Because they are translucent and very hard at room temperature. This prevents scratches.

**Exercise N°3**  
6 pts



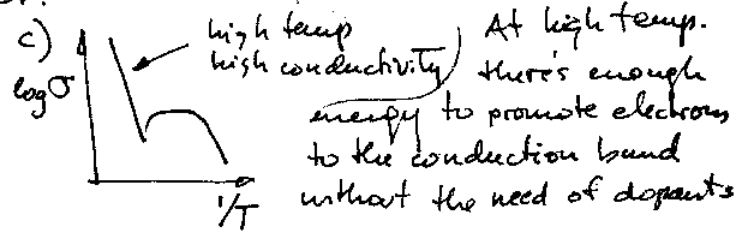
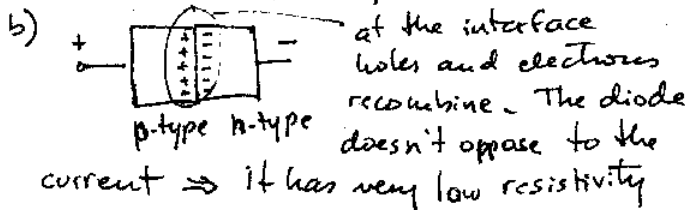
In the electronics industry, semiconductors like Si and Ge are "doped" using elements like Al, P, Ga, etc. A high purity silicon wafer is doped with ~~aluminum~~ at 1250°C for the fabrication of a diode. By design requirements, at a depth of 0.7 μm from the surface there should be 10<sup>-5</sup> at.% Ga.

- 1.0 a) What type of semiconductor has been produced *n*-type or *p*-type? Justify your answer.
- 1.0 b) If this semiconductor is mounted in *p-n* diode, and the diode is connected to the positive pole of a battery the diode will have very high or very low electrical resistance? Explain.
- 1.0 c) Why at high temperature this extrinsic semiconductor behaves like an intrinsic one?
- 3.0 d) Assuming that the concentration of Ga at the surface is 6 · 10<sup>-5</sup> at.% Ga, calculate the time necessary to produce this diode part.

Bonus (2pts): Without doing any calculation, (at the same temperature) indicate for

aluminum if the required time would be shorter or longer than for Ga. Justify your answer briefly. How is the activation energy for diffusion of Al in Si with respect to that of Ga in Si?

a) Ga is in the group IIIA of the periodic table. This means that Ga has one less electron than Si ⇒ it will form holes (+) as charge carriers. In other words this is a *p*-type semiconductor.



z	erf z	z	erf z	z	erf z	z	erf z
0	0	0.40	0.4284	0.85	0.7707	1.6	0.9763
0.025	0.0282	0.45	0.4755	0.90	0.7970	1.7	0.9838
0.05	0.0564	0.5	0.5205	0.95	0.8209	1.8	0.9891
0.10	0.1125	0.55	0.5633	1.0	0.8427	1.9	0.9928
0.15	0.1680	0.6	0.6039	1.1	0.8802	2.0	0.9953
0.20	0.2227	0.65	0.6420	1.2	0.9103	2.2	0.9981
0.25	0.2763	0.70	0.6778	1.3	0.9340	2.4	0.9993
0.30	0.3286	0.75	0.7112	1.4	0.9523	2.6	0.9998
0.35	0.3794	0.80	0.7421	1.5	0.9661	2.8	0.9999

d)  $C_x = 10^{-5}$  at.% Ga

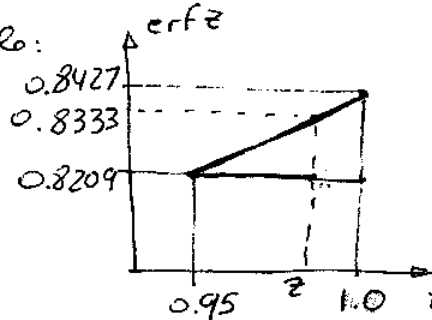
$C_s = 6 \times 10^{-5}$  at.% Ga

$C_0 = 0$

$$\frac{C_s - C_x}{C_s - C_0} = \frac{5 \times 10^{-5}}{6 \times 10^{-5}} = 0.833 = \operatorname{erf}\left(\frac{x}{2\sqrt{Dt}}\right)$$

$$\frac{x}{2\sqrt{Dt}} = z \Rightarrow \frac{x}{2\sqrt{D}z} = \sqrt{t} \therefore t = \frac{1}{D} \frac{x^2}{4z^2}$$

From the table:



$$\frac{z - 0.95}{1.0 - 0.95} = \frac{0.8333 - 0.8209}{0.8427 - 0.8209}$$

$$z = 0.95 + \frac{0.0124}{0.0218} \times 0.05$$

$$z = 0.9785$$

$D$  is from the graph @  $1,250^\circ\text{C}$  ( $\frac{1}{T} \approx 0.00065 \text{ K}^{-1}$ ),  $D \approx 10^{-11} \frac{\text{cm}^2}{\text{s}}$

$$x = 0.7 \mu\text{m} = 0.7 \times 10^{-6} \text{m} = 0.7 \times 10^{-4} \text{cm}$$

$$t = \frac{1}{10^{-11} \frac{\text{cm}^2}{\text{s}}} \times \frac{(0.7 \times 10^{-4} \text{cm})^2}{4 \times (0.9785)^2} = 127.9 \text{ sec.}$$

$$t \approx 2.13 \text{ min.}$$

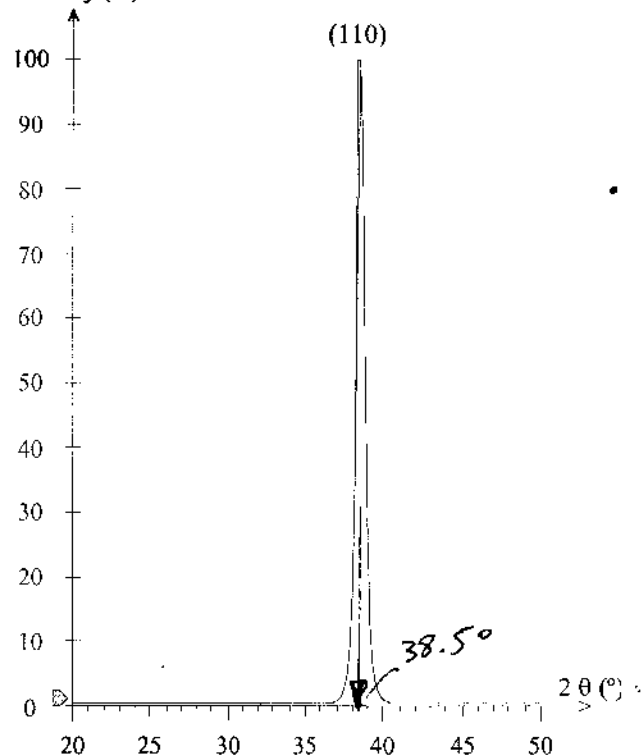
e) At the same temp., Al diffuses faster than Ga in Si because the diffusivity is higher  $\Rightarrow$  shorter times.

Bonus: Both activation energies are similar (the slopes of both straight lines are similar  $\Rightarrow$  parallel lines).

## Exercise N°4

5 pts.

Intensity (%)



Niobium (Nb) is an alloying element used in steels to improve their mechanical properties and corrosion resistance. The following is a partial x-ray diffraction obtained for pure Nb using  $\text{Cu-K}\alpha$  ( $\lambda = 0.1540562 \text{ nm}$ ).

- What unit cell does niobium have?
- Calculate the interplanar spacing  $d_{110}$ .
- Calculate the lattice parameter of Nb.
- Indicate at what value of  $2\theta$  you should expect the next peak to appear.

Bonus (1pt.): Suppose you increase the temperature of your Nb sample, will the position and shape of the peak change? Explain carefully.

a) The (110) is the first to show up <sup>in the  $2\theta$  scale</sup>  $\Rightarrow$  then this is a BCC unit cell.

b) Bragg's law =  $\lambda = 2d \sin \theta$

$$d_{110} = \frac{\lambda}{2 \sin \theta} = \frac{0.1540562 \text{ nm}}{2 \times \sin 38.5^\circ} = 0.2336 \text{ nm}$$

$$c) d_{110} = \frac{a}{\sqrt{1^2 + 1^2 + 0^2}} = \frac{a}{\sqrt{2}} \therefore a = d_{110} \times \sqrt{2}$$

$$a = 0.2336 \times \sqrt{2} \text{ nm} = 0.3304 \text{ nm}$$

d) The next peak should show up for  $2\theta_2$ :  $\frac{\sin^2 \theta_1}{\sin^2 \theta_2} \approx 0.5$

$$\therefore \sin \theta_2 = \frac{\sin \theta_1}{\sqrt{0.5}} \therefore 2\theta_2 = 2 \arcsin \left( \frac{\sin(38.5/2)}{\sqrt{0.5}} \right) = 55.6^\circ$$

Bonus: Yes, both position and shape will change. Since there's an expansion of the cell, the interplanar distances will change so the position of the peak will shift. As the vibration of the lattice increases the peak will widen.

## Exercise N°1

2 pts.

Consider the cases of titanium, vanadium and chromium. These elements are common in the fabrication of high temperature applications. Predict and rank (from highest to lowest) the solubilities between:

- Titanium in vanadium
- Vanadium in chromium
- Chromium in titanium.

Justify your answer. Remember that  $4R = \sqrt{2} \cdot a$  for FCC and  $2R = a$  for HCP.

Z=22	A=47.90
<b>Ti</b>	
HCP	
$a = 0.29504 \text{ nm}$	
$c = 0.46833 \text{ nm}$	

Z=23	A=50.94
<b>V</b>	
BCC	
$a = 0.3039 \text{ nm}$	

Z=24	A=52.00
<b>Cr</b>	
BCC	
$a = 0.28846 \text{ nm}$	

Continue your work on the back of the paper

check for differences in radii -

$$R_{Ti} = \frac{a_{Ti}}{2} = \frac{0.29504 \text{ nm}}{2} = 0.14752 \text{ nm}$$

$$R_V = \frac{\sqrt{3} a_V}{4} = \frac{\sqrt{3}}{4} \times 0.3039 \text{ nm} = 0.131593 \text{ nm}$$

$$R_{Cr} = \frac{\sqrt{3} a_{Cr}}{4} = \frac{\sqrt{3}}{4} \times 0.28846 \text{ nm} = 0.124907 \text{ nm}$$

a) Ti  $\rightarrow$  V:

$$\frac{R_V - R_{Ti}}{R_{Ti}} \times 100 = \frac{0.131593 - 0.14752}{0.14752} \times 100 = -12.10\%$$

b) V  $\rightarrow$  Cr:

$$\frac{R_{Cr} - R_V}{R_{Cr}} \times 100 = \frac{0.124907 - 0.131593}{0.124907} \times 100 = -5.35\%$$

c) Cr  $\rightarrow$  Ti:

$$\frac{R_{Ti} - R_{Cr}}{R_{Ti}} \times 100 = \frac{0.14752 - 0.124907}{0.14752} \times 100 = 15.32\%$$

Applying Hume-Rothery's rules:

highest solubility (little size difference + same crystal structure): V  $\rightarrow$  Cr

middle solubility (size difference): Ti  $\rightarrow$  V

lowest solubility (largest size diff. different crystal str.): Cr  $\rightarrow$  Ti

INGE 4001 – Sections: 016 & 036

Instructor: O. M. Suárez – Grad Student Assistant: Hermes Calderón

Mid-Term Exam #2, Thursday March 15, 6:00pm, Stéfani S-113

Maximum time: 1½ hours - Maximum Grade: 25 pts. (+4 bonus points built-in)

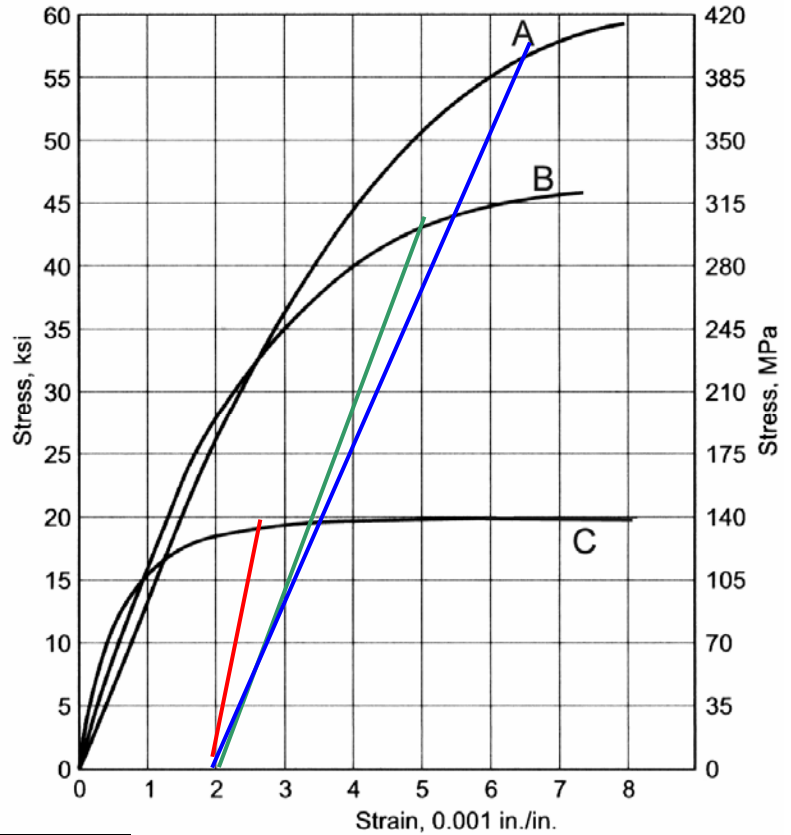
Name:

Student Number:

**Exercise N°1** 8 pts.

Forged brass is a common, inexpensive Cu alloy. The tensile curves on the right correspond to brass containing 60% Cu, 38% Zn and 2% Pb with different treatments. Sample A was cold-rolled to 17.5% and sample B was also cold-rolled but to 8.5%. Sample C was cold-rolled to 17.5% (like sample A) and then annealed at certain temperature. Respond to the following requests:

- a) Calculate the UTS in MPa of all samples
- b) Estimate the  $\sigma_{0.2}$  (approximately) in MPa of all samples
- c) Estimate E in GPa in all samples
- d) Compute the ductility (%) in all samples
- e) Compute toughness ( $\text{MJ/m}^3$ ) in all samples



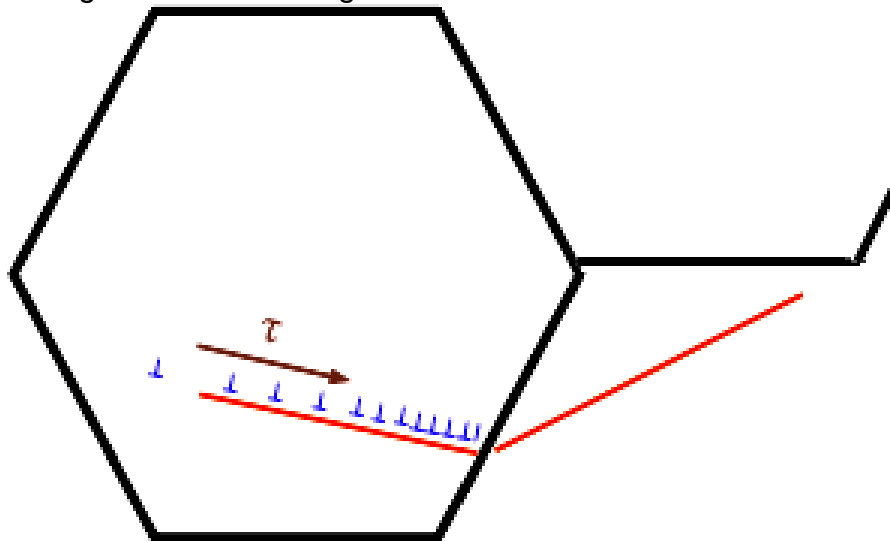
Sample	UTS (MPa)	$\sigma_{0.2}$ (MPa)	E (GPa)	$\delta$ (%)	Toughness ( $\text{MJ/m}^3$ )
A	416.7	389.4	95.97	0.79	2.16
B	321.8	301.3	100.68	0.73	1.73
C	140.3	134.7	156.13	0.81	1.02

All these properties were calculated with Excel. *The elastic modulus is hard to measure here; if you reported all of them with similar values, that's ok.*

**Exercise N°2** 9 pt.

The following questions and requests may or may not be related to each other.

- a) Use the sketch on the right to respond to the following requests:
- Explain the dislocation pile-up on a grain boundary. What is the role of shear stresses during the process?
  - Can the dislocations “jump” into the next grain? Is there any exception to your response? Explain.
  - The applied shear stress is higher, lower or equal to the theoretical resolved shear stress?
  - What is the Peierls-Nabarro shear stress? Is it a realistic approximation? Why or why not.
- b) Now refer to the sphere on the right. Suppose it is an undeformed metallic grain that is to be deformed via cold rolling.
- Sketch the effect of the cold working on the grain.
  - What happened to the grain volume after cold rolling?
  - What happened to the grain surface and grain boundary?
  - What happened to the dislocation density of the deformed grain?
  - If you measure microhardness on the undeformed grain and in the deformed one, what changes would you expect?
- c) Go back to **Exercise 1** and respond very carefully to the following questions:
- Why samples A and B have so different UTS values?
  - Why samples A and C have so different UTS values?
  - What type of annealing did sample C have: stress-relief (recovery) or recrystallization? Explain.
- d) In the reading assignment you learned about glass strengthening. In five sentences summarize how a glass can be strengthened.



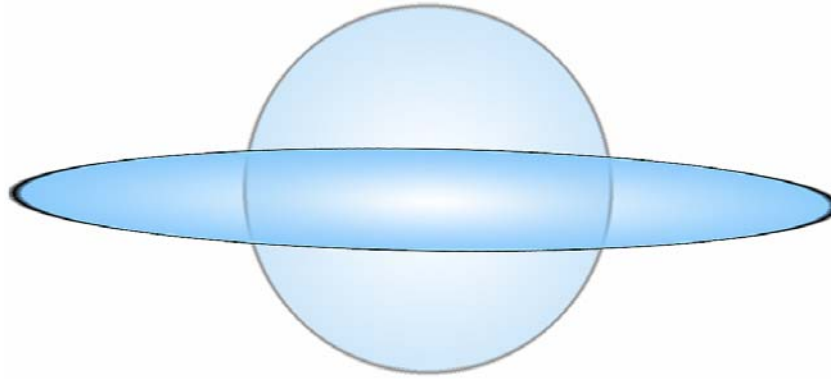
- a) In the figure, red lines represent slip plane and directions (systems) on two contiguous grains. Dislocations slide on them when a shear stress is applied. Since the orientation of the slip system in the next grain is different,  $\tau$  cannot force the dislocations to jump onto the next grain. They start accumulating next to the grain boundary (dislocation pile-up) as long as there are shear stresses still applied along the slip system. This applied stress is much lower

than the theoretical critical resolved shear stress ( $\sim 1000$  times smaller). The Peierls-Nabarro shear stress  $\tau_{PN}$  is a calculation of the critical resolved shear stress when the presence of dislocations is considered.

- b) The effect of the cold working on the grain is presented in the figure
- The grain volume after cold rolling has not been heavily affected. Most atoms contained in the undeformed grain are present in the deformed one.
  - The grain surface is much higher for this flattened body since a sphere is the geometrical body that exposes the smallest area to contain a given volume. As the grain approaches a flat surface, the resulting surface area becomes larger. As a consequence, the amount of grain boundaries in a cold worked polycrystalline metal is much higher.

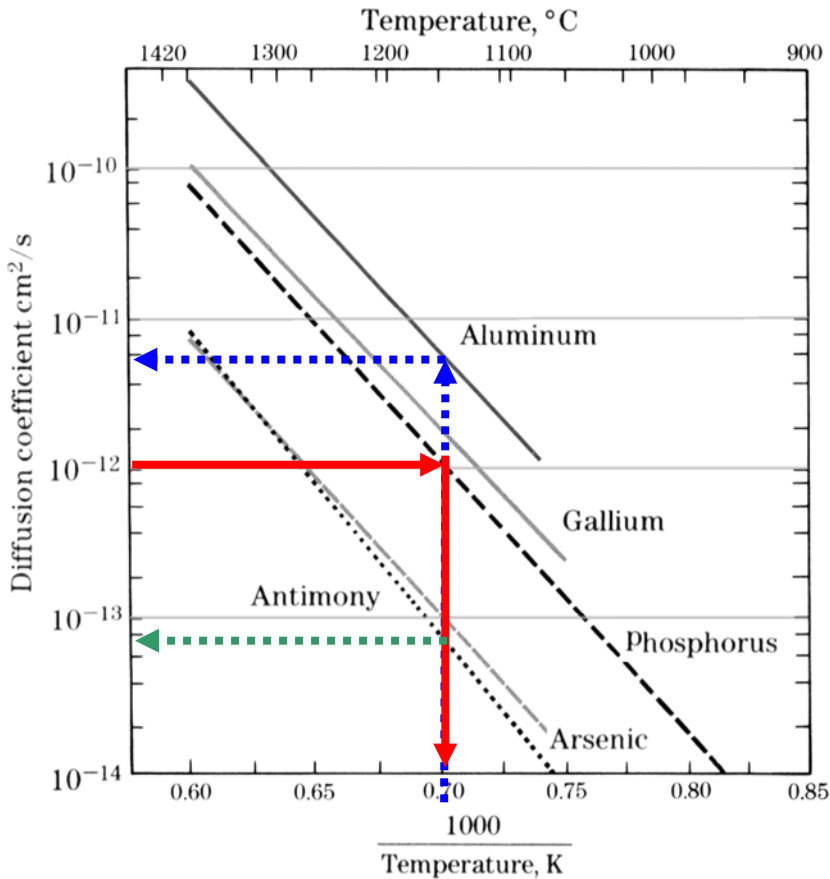


- To accommodate the same amount of atoms in the deformed grain the dislocation density has to be much higher. Plenty of defects are introduced in the cold worked metal.
- Microhardness measured in the undeformed grain has to be much higher due to strain hardening occurring upon cold working in the metal.



- c) i. Sample A was cold-rolled twice as much as sample C. Sample A underwent a much larger strain hardening than sample B, resulting in higher values of UTS.  
ii. Sample C went through an annealing process which provides it with less strength but increases its ductility by relieving some internal stresses.  
iii. The amount of ductility gained after the annealing is very small but there is a substantial decrease in UTS. So, most likely this sample had a high temperature stress-relief (recovery) annealing or perhaps an incipient recrystallization process. *Your answer will be evaluated according to how sound your reasoning was to analyze this situation.*
- d) The article recalls that Griffith discovered the source of glass weakness: the surface conditions. Other researchers discovered the damaging effect of tiny cracks on glass strength. The author proposes to concentrate efforts by analyzing the surface and few angstroms (tenths of nanometers) deep. Then he proposes to heal those flaws and protect the glass surface from further damage.

## Exercise N°3 6 pts.



In the electronics industry, semiconductors like Si and Ge are “doped” using elements like P, Ga etc. A high purity silicon wafer ( $C_0=0$ ) is doped with phosphorus (group VA in the periodic table) for the fabrication of a diode. By design requirements, at a depth of  $1.6 \mu\text{m}$  from the surface there should be  $10^{-6}$  at.% P. For economic reasons the doping process should not exceed 22 minutes.

- Assuming that the concentration of P at the surface is  $5 \cdot 10^{-4}$  at.% P, calculate the minimum temperature necessary to produce this diode part.
- Without doing any calculation, (at the same temperature) indicate for aluminum if the required time would be shorter or longer. Do the same for antimony (group VA). Justify your answer briefly.
- Why was Fick's second law (and not the first law) used to describe this diffusion phenomenon?
- Please use Fick's first law expression and relate it to other phenomenological equations such as heat conduction. What would be the driving forces in

both cases? How about the mobility property?

a)  $(C_s - C_x)/(C_s - C_0) = 0.998 = \text{erf}(z)$ . Interpolating for the intervals shown in yellow, we obtain

z	erf z	z	erf z	z	erf z	z	erf z
0	0	0.40	0.4284	0.85	0.7707	1.6	0.9763
0.025	0.0282	0.45	0.4755	0.90	0.7970	1.7	0.9838
0.05	0.0564	0.5	0.5205	0.95	0.8209	1.8	0.9891
0.10	0.1125	0.55	0.5633	1.0	0.8427	1.9	0.9928
0.15	0.1680	0.6	0.6039	1.1	0.8802	2.0	0.9953
0.20	0.2227	0.65	0.6420	1.2	0.9103	2.2	0.9981
0.25	0.2763	0.70	0.6778	1.3	0.9340	2.4	0.9993
0.30	0.3286	0.75	0.7112	1.4	0.9523	2.6	0.9998
0.35	0.3794	0.80	0.7421	1.5	0.9661	2.8	0.9999

$z = 2.18512$ . Then substituting  $t = 22 \text{ min} = 1,320\text{s}$  and  $x = 1.6 \cdot 10^{-6}\text{m}$ , we obtain that:  
 $D = 1.0154 \cdot 10^{-16} \text{m} \cdot \text{s}^{-2}$ . However the plot is in  $[\text{cm} \cdot \text{s}^{-2}]$ , so the diffusivity would be:  $D = 1.0154 \cdot 10^{-12} \text{cm} \cdot \text{s}^{-2}$ .  
 With this value from the line corresponding to phosphorus (red arrows) we obtain a value of  $1/T = 0.0007$ ; therefore the temperature should be:  $T =$

$$1,428.6\text{K} - 273 = 1,155.6^\circ\text{C}$$

b) The dotted blue arrows indicate that at the same temperature, the diffusivity of Al in silicon is higher. Therefore the time required for the same diffusion situation would be shorter. In the case of Sb (dotted green arrows) it would require more time as the diffusion coefficient of Sb in Si is smaller.

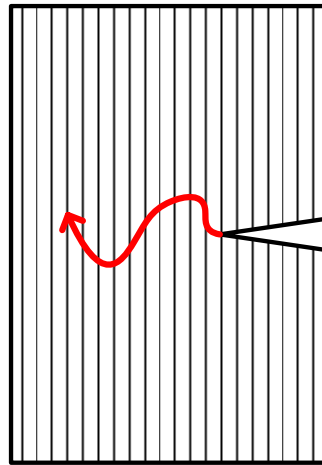
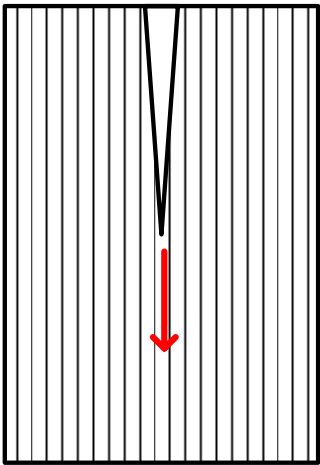
c) Fick's second law of diffusion is used for processes that are not in steady-state, i.e. time is an important factor as it affects the concentration of the diffusing species.

d)  $J = D \cdot \partial C / \partial x$ , where J is the flux of atoms per unit area and unit time. The diffusivity of diffusion coefficient D measures the mobility of the diffusing (moving) atoms into the solvent crystal. The concentration gradient  $\partial C / \partial x$ , represents the driving force for the diffusion phenomenon.

**Exercise N°4** 6 pts.

The following questions and requests may or may not be related to each other. Use sketches to clarify your responses.

- Explain the class demonstration about the effect of a crack (tearing) on a paper. What was its purpose? What was the conclusion drawn from the experiment?
- Explain the polygonization process upon recovery.
- What is the relation between self-diffusion activation energy and the melting point of pure metals? Justify your answer.
- Based on your previous answer, would you expect a relation between those melting points and the elastic modulus (Young's modulus) of different metals? Why or why not.
- Explain the mechanism by which solute atoms help strengthen a pure metal.
- Explain briefly why ionic solids are difficult to deform plastically.



a) When the paper fibers are parallel to the tear (crack) this propagates more or less straightly. The paper doesn't offer much resistance to crack propagation (low  $K_{IIIc}$ ). When the paper fiber are perpendicular (right sketch) to the crack, this doesn't have a straight path. Therefore energy is lost to propagate the crack (higher  $K_{IIIc}$ ).

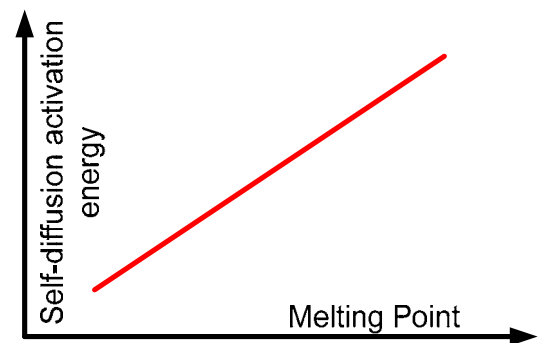
b) Polygonization occurs during recovery annealing. Atoms move a short distance favoring the alignment of dislocations (one below the next one). This alignment creates a low-angle grain boundary. Dislocations align so as to try to cancel out positive and negative stress fields associated with them.

c) The self-diffusion activation energy increases almost linearly for increasing values of melting points of pure metals. The melting point measures the stability of the solid. A more rigid structure (higher MP) then requires more energy to form a vacancy or to promote an atom jump (diffusion).

d) the higher melting point of a pure element, the higher the interatomic bond energy. Therefore, since the elastic modulus measures the rigidity of a solid, this should be higher in higher melting point elements.

e) Solute atoms help "trap" dislocations, which are pinned down by the presence of those atoms. However, the strengthening is not quite high since a small increase in the applied shear stress will force the dislocation to keep sliding along its slip system.

f) Plastic deformation depends on how easy dislocation slides under an applied  $\tau$ . When dislocations try to cut through an ionic crystals, it alters the symmetry of those crystals. Ions with similar charges then are forced to come closer and they repel each other. The dislocation motion is then much more difficult and would require higher values applied  $\tau$ , which could also cause a local crack. As a result, ionic crystals are brittle in general (difficult to deform plastically).



## INGE 4001 – Sections: 066 &amp; 076

Instructor: O. M. Suárez – Grad Student Assistant: Hermes Calderón

Mid-Term Exam #2, Tuesday Oct. 17, 6:00pm, Stéfani S-113

Maximum time: 1½ hours - Maximum Grade: 30 pts.

Name:

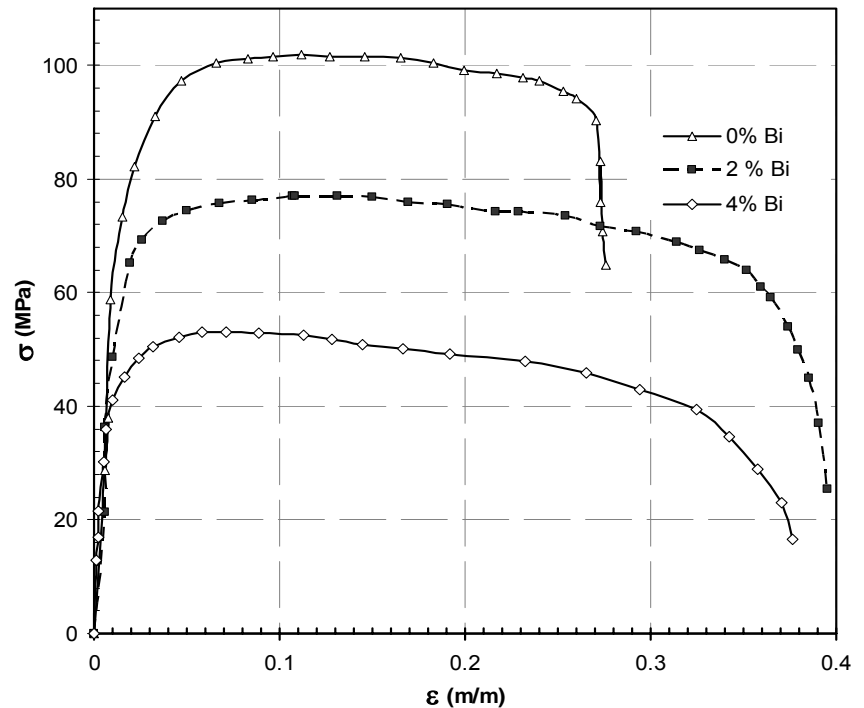
Student Number:

**Exercise N°1** 10 pts.

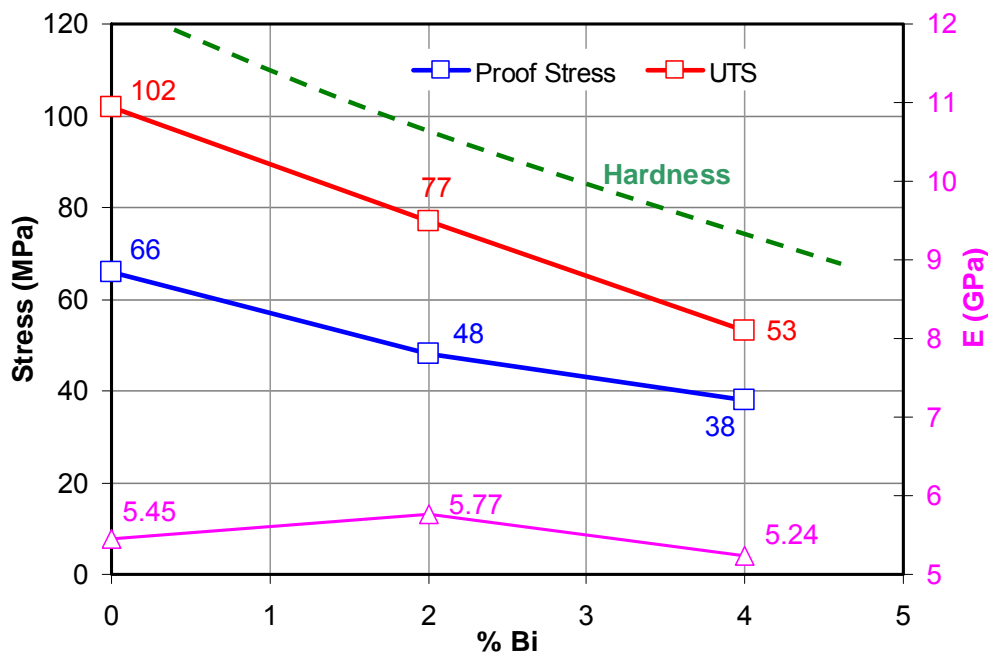
Sn-3.5%Ag-0.7%Cu soldering alloys are being investigated to replace tin alloys containing lead. Small amounts of bismuth (Bi) added to those new alloys, modify their mechanical properties (tensile curves on the right). You are asked to produce *calculated* graphs of the following mechanical properties as a function of the amount of Bi in the Sn-3.5%Ag-0.7%Cu alloys:

- UTS
- $\sigma_{0.2}$  (approximately)
- E (approximately)
- Ductility (%)
- Toughness ( $\text{MJ/m}^3$ )
- Hardness (no calculation required)

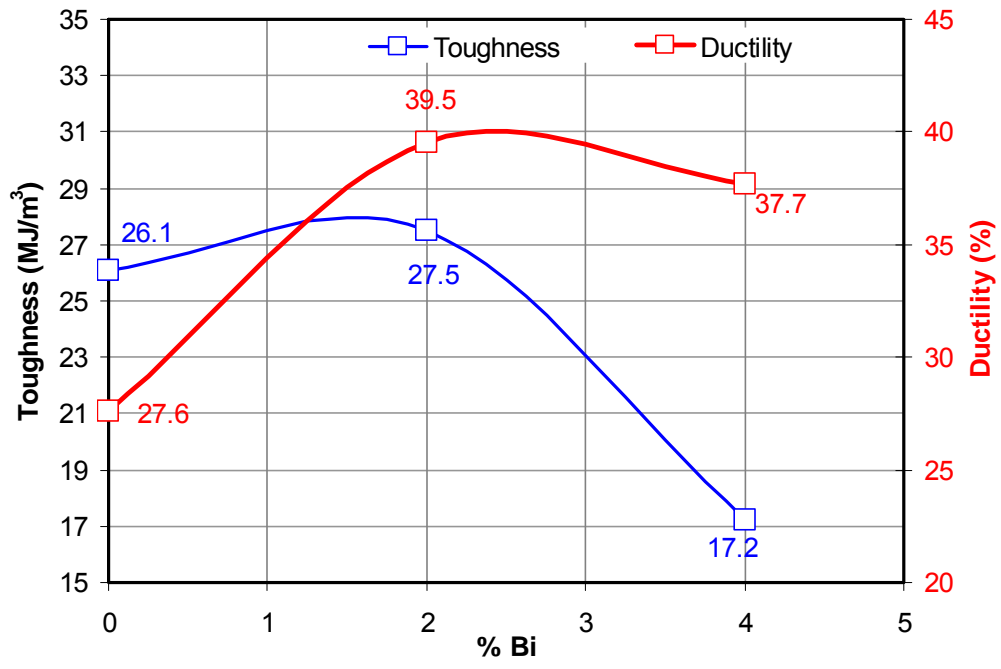
Your graphs must be as accurate as possible. Also please label each data point with the corresponding value as calculated.



*Metall. and Materials Trans. A, 36 [6], 2005, pp. 1439-1446*



Although we cannot extract the values of hardness from the tensile test plots we can say that hardness varies in the same way as YS or UTS (green dashed line) as a function of percent bismuth. On the other hand, the elastic modulus remains almost constant since it is not much affected by small changes in chemical composition (as discussed in class).



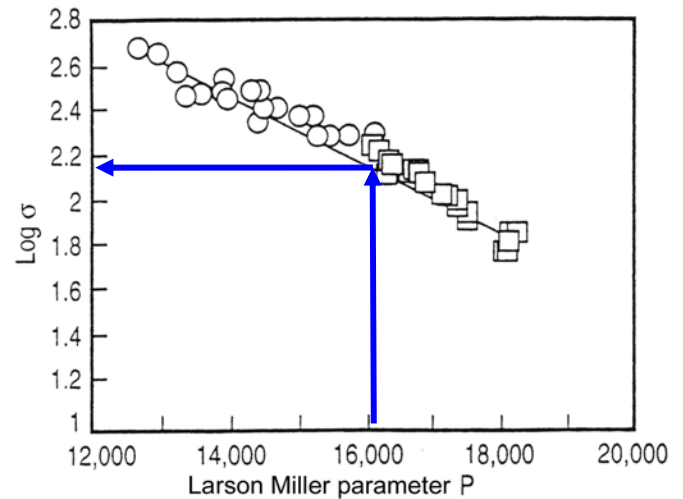
**Exercise N°2** 6 pts.

- a) A cylindrical container of radioactive waste is made of a Zr alloy Zircaloy-4. The radioactive waste is at 290°C and 32 atmospheres of pressure. The container radius is 80 cm. If the waste has a disintegration time of 50,000 years, please estimate the minimum thickness of the container that would make it *barely* safe. The stress generated by the internal pressure in a cylindrical container can be estimated as:

$$\sigma = \frac{(\text{pressure}) \cdot (\text{radius})}{\text{thickness}}$$

In the figure on the right,  $\sigma$  is given in MPa, and the Larsen-Miller parameter is defined as  $P = T(20 + \log t_R)$ , where  $T$  is the temperature in degrees Kelvin,  $t_R$  is the time to rupture in hours.

- 0.1013 MPa = 1 atm. There was a mistake in the conversion factor which will be considered in the exam correction.*
- b) What is the Nabarro-Herring creep? At what temperature does this creep mechanism activate? (four sentences + sketch)
- c) What is the difference between a creep testing machine and a regular tensile testing one?



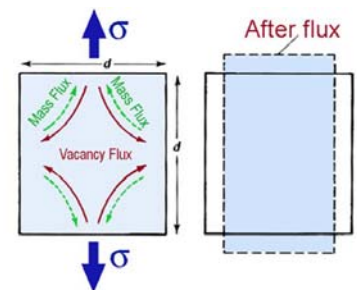
*JOM, 52 [9], 2000, pp. 39-41.*

a)  $t_R = 50,000 \text{ years} = 4.38 \cdot 10^8 \text{ hours}$   
 $T = 290 + 273 = 563\text{K}$   
 Pressure = 32 MPa · 0.1013 = 3.24 MPa

$P = 563 (20 + \log 4.38 \cdot 10^8) = 16,125$   
 From the graph:  $\log \sigma \cong 2.15$  then  $\sigma = 141.25 \text{ MPa}$ .

Thickness =  $\frac{(\text{pressure}) \cdot (\text{radius})}{\sigma} = \frac{3.24 \text{ MPa} \cdot 0.80 \text{ m}}{141.25 \text{ MPa}} = 0.1834 \text{ m} = 18.34 \text{ cm}$

b) Nabarro-Herring creep is also called diffusional creep as it is heavily assisted by diffusion mechanisms: Under uniaxial tensile stress there is a flow of vacancies from the top and bottom of a grain to the lateral walls, which allows atoms from those lateral wall to diffuse up to the top and bottom of that grain. Since diffusion is the main responsible for the N-B creep, for this to occur the material has to be at very high temperatures.



c) In a regular tensile test, the moving crosshead imposes a deformation at very low speed (to avoid strain-rate sensitivity and simulate static loading). Therefore, the stress applied to the sample varies at all times. In a creep testing machine the load (stress) is constant and is applied through a lever mechanism by a dead weight.

**Exercise N°3** 6 pts.

- a) A 1020 steel gear is carburized at 928°C for 7 hours. After the treatment what would the carbon percent be at 0.35mm below the surface? Assume that the carbon content of the surface is 0.95% and the steel contains initially 0.20% C. The diffusion coefficient of carbon in iron at that temperature is:  $1.28 \cdot 10^{-11} \text{ m}^2/\text{s}$ .

z	erf z	z	erf z	z	erf z	z	erf z
0	0	0.40	0.4284	0.85	0.7707	1.6	0.9763
0.025	0.0282	0.45	0.4755	0.90	0.7970	1.7	0.9838
0.05	0.0564	0.5	0.5205	0.95	0.8209	1.8	0.9891
0.10	0.1125	0.55	0.5633	1.0	0.8427	1.9	0.9928
0.15	0.1680	0.6	0.6039	1.1	0.8802	2.0	0.9953
0.20	0.2227	0.65	0.6420	1.2	0.9103	2.2	0.9981
0.25	0.2763	0.70	0.6778	1.3	0.9340	2.4	0.9993
0.30	0.3286	0.75	0.7112	1.4	0.9523	2.6	0.9998
0.35	0.3794	0.80	0.7421	1.5	0.9661	2.8	0.9999

- b) Sketch the carbon composition as a function of the distance to the surface.  
 c) Sketch the hardness measured as a function of the distance to the surface.  
 d) What is the driving force in a diffusion process?  
 e) Why would you expect faster diffusion of solutes in a polycrystalline metal than in a single crystal? (three sentences + sketch)  
 f) At the same temperature, with a small concentration of vacancies, which solute would diffuse faster in a metal: an interstitial atom or a substitutional atom? Explain briefly.

a)  $C_0 = 0.20 \text{ wt.}\%$     $C_S = 0.95 \text{ wt.}\%$     $C_x = ?$

$t = 7 \text{ hours} = 25,200 \text{ s}$

$D = 1.28 \cdot 10^{-11} \text{ m}^2/\text{s}$

$z = \frac{0.00035 \text{ m}}{2 \sqrt{25200 \text{ s} \cdot 1.28 \cdot 10^{-11} \text{ m}^2/\text{s}}} = 0.30813$  by linear interpolation then  $\text{erf}(0.30813) = 0.33699$

$\frac{0.95 - C_x}{0.95 - 0.20} = 0.33699$  then  $C_x = 0.95 - 0.33699 \cdot (0.95 - 0.20) = 0.70$

b) We have three points to produce the curve:

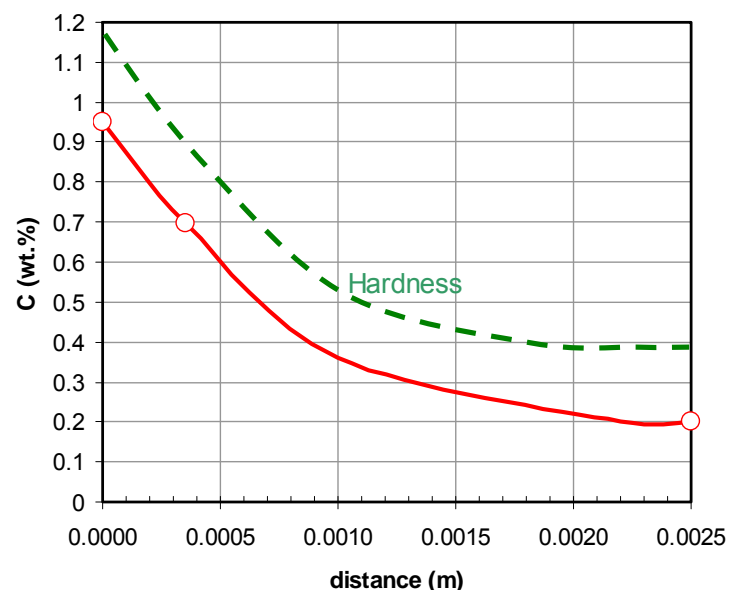
c) Hardness varies like the amount of carbon: less carbon  $\equiv$  lower hardness.

d) Recalling Fick's First Law:  $J = -D \frac{dC}{dx}$  then the driving

force for diffusion is the concentration gradient  $\frac{dC}{dx}$ . No gradient means no net diffusion.

e) Grain boundaries represent regions with high energy in which atoms are somewhat in a disarray. It is possible that diffusing solute atoms can travel faster along those grain boundaries. Then diffusion coefficients in polycrystalline solids should be higher than in single crystals.

f) Interstitial solutes will diffuse faster since they don't need to be assisted by vacancies. The atoms are so small that they funnel through the solvent crystal interstices. Then diffusivity of interstitial solutes should be higher than substitutional ones.

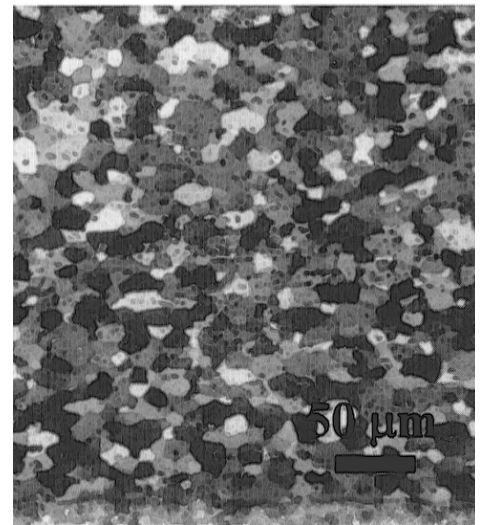
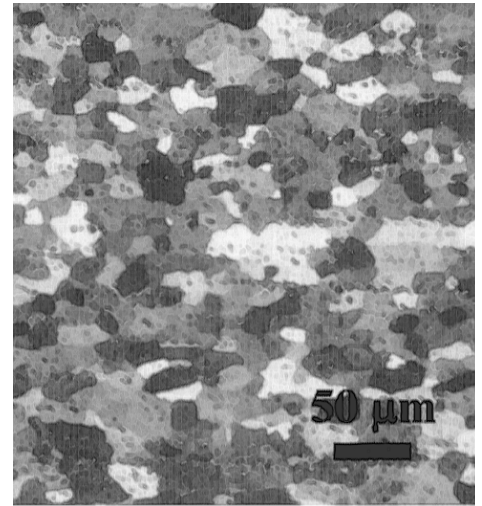




**Exercise N°4** 8 pt.

The following questions and requests may or may not be related to each other.

- a) The microstructures on the left correspond to two sheets made of an Al-Mn-Mg alloy. The alloy at the top was **70%** cold worked and then annealed at 450°C for 0.5 hours. The one at the bottom was **90%** cold worked and then annealed at 450°C for 0.5 hours. Please explain the differences in microstructure in four sentences. What is the name of this annealing treatment?
- b) How does cold working affect UTS, YS, and ductility of a metallic material?
- c) Briefly explain the role of dislocations in cold-working.
- d) Explain the difference between the theoretical critical resolved shear stress and the Peierls shear stress.
- e) Indicate with a check mark (✓) what would happen to the endurance limit of a steel part:

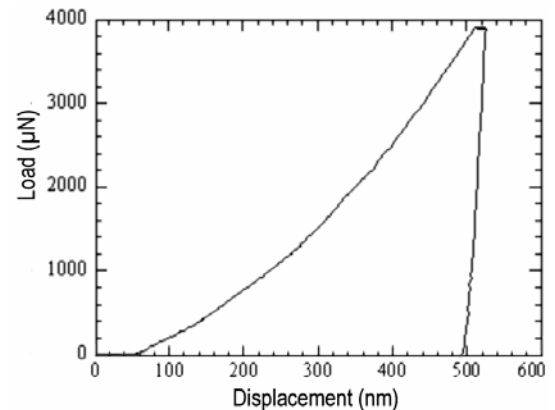


*Met. Trans. A. 37A [6], 2006, p. 1891*

	Increases	Decreases	Don't know / don't care
If the surface is hardened by a surface treatment	X		
If the surface is carefully polished (excellent finishing)	X		
If the surface is corroded		X	
If the material is softened by annealing		X	

**Bonus (4 pts.):** The nanoindentation curve on the right was obtained at the U. of Wisconsin on one of our Al-B-Mg composites using a Berkovich indenter.

- i) Explain the elastic-inelastic regions.
- ii) Can you obtain the elastic modulus from this data? Which part of the curve?
- iii) What is a Berkovich indenter?
- iv) Is the instrument sensitive to the state of the indenter? Explain.



*P. Resto et al., [unpublished work]*

a) Clearly the alloy on top has larger grain size. Since it was subject to a smaller cold work and was subject to a similar recrystallization annealing then we can draw some conclusions: Higher cold work introduces a larger number of dislocation per unit volume (high dislocation density), and increases the amount of grain boundaries (remember the explanation on surface difference between a sphere and an elongated grain given in class). Both are nucleation sites for new, recrystallized grains. Since the amount of nucleation sites is larger, then the recrystallized grains are smaller, which is what happened to the alloy in the bottom.



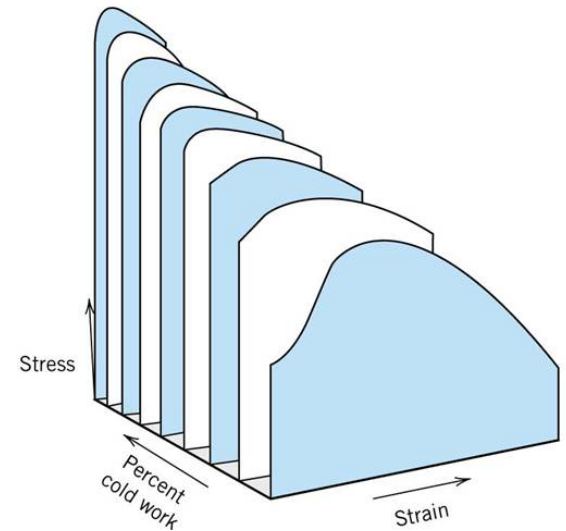
b) Clearly from the image on the right, as cold working increases, UTS increases, YS (or  $\sigma_{0.2}$ ) increases, and ductility (or elongation to failure) decreases.

c) Cold-working increases dislocation density, i.e. the number of dislocation per unit volume, which reduces the toughness and ductility of the metal. Dislocations have more chances to interact among themselves and become obstacles, which translates into a harder material.

d) The theoretical critical resolved shear stress  $\tau_C$  is

approximately  $\tau_C \approx \frac{G}{5}$  a very much higher value of the minimum shear stress that would provoke a plastic deformation in a single crystal when no dislocation is present. On the other hand, the

Peierls stress considers the presence of dislocations and becomes much lower:  $\tau_P \approx \frac{G}{180}$ , which is almost three orders of magnitude smaller than  $\tau_C$ .

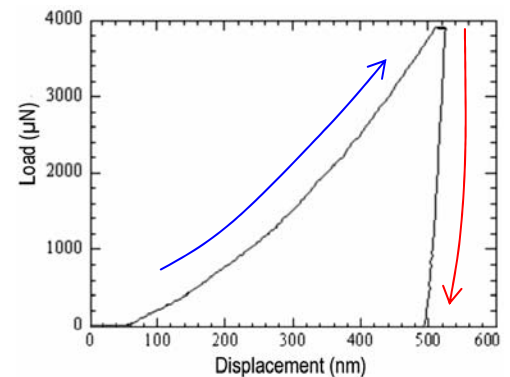
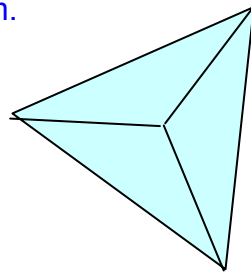


#### Bonus:

i) The inelastic region corresponds to the loading part of the curve (in blue) when the plastic deformation is induced. The elastic part corresponds to the recovery upon unloading the indenter (red arrow).

ii) The elastic modulus of the particle can be obtained from the unloading curve since it is elastic and establish a relation between load and deformation.

ii) The Berkovich indenter is a diamond tip with a pyramidal form with a equilateral triangular form.



iv) The instrument is extremely sensitive to the state of the indenter. Small imperfection such as rounding of tip (due to long time use), or tiny particles stuck to it can alter the measurements.