UNIVERSITY OF CALIFORNIA
College of Engineering
Department of Materials Science & Engineering

Professor R. Gronsky

Fall Semester, 2005

Engineering 45 Midterm 02

SOLUTIONS

INSTRUCTIONS

LATTICE seating.................Please be seated with *occupied* seats to your front and back, *vacant* seats to your left and right.

CLOSED BOOK format...... All you need are writing instruments and a straightedge. Please store all books, reference materials, calculators, PDAs, cell phones (OFF), and iPods.

NO DISRUPTION rule.........Questions cause too much of a disturbance to others in the room. Instead of asking questions, write any concerns or alternative interpretations in your answers.

PROFESSIONAL protocol...Engineers do not cheat on the job and they certainly don’t cheat on exams.

Do not open until “START” is announced.

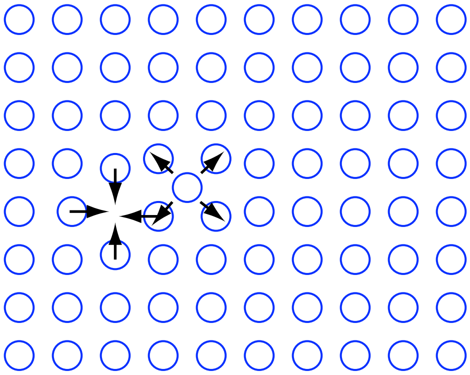
1. Defects in Solids (10 points)

Mark ☒ the ballot box corresponding to the best answer. Two (**+2**) points for correct answers, **-1** if wrong, **0** if blank.

(**a**) Point defects in solids include

☒ vacancies
☐ dislocations
☐ both

(**b**) The defect known as a "Frenkel pair" is shown in this sketch to have



☐ body-centered symmetry
☒ an extended strain field
☐ both

(**c**) Vacancies in solids

☐ participate in diffusion
☐ increase the entropy of a material
☒ both

(**d**) Dislocations in solids

☒ participate in plastic deformation
☐ decrease the entropy of a material
☐ both

(**e**) Fick's First Law for diffusion flux

$$J_x = -D\,\frac{\partial c}{\partial x}$$

expresses the fact that

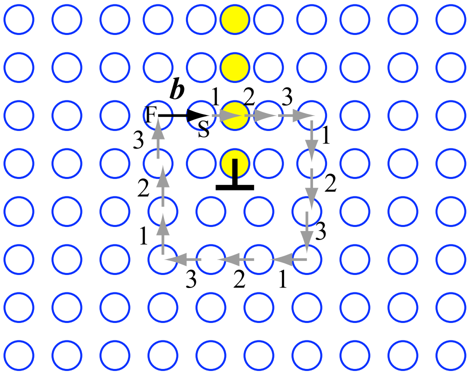
☐ diffusion requires a negative diffusivity
☒ mass flows down a concentration gradient
☐ both

2. Defects in Solids (10 points)

For this problem you must draw and label all requested features directly on the figures provided.

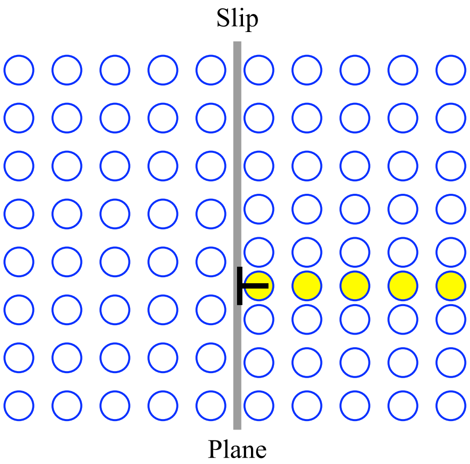
(**a**) (**2 points**) Fill in the atoms comprising the extra-half plane and label with the conventional symbol (⊥) the edge of the extra half-plane that establishes the line direction vector of the edge dislocation shown below.

(**b**) (**3 points**) On the same figure below, trace and label a Burgers circuit in finish-start-right-hand (FSRH) convention, and identify the resulting Burgers vector (***b***).



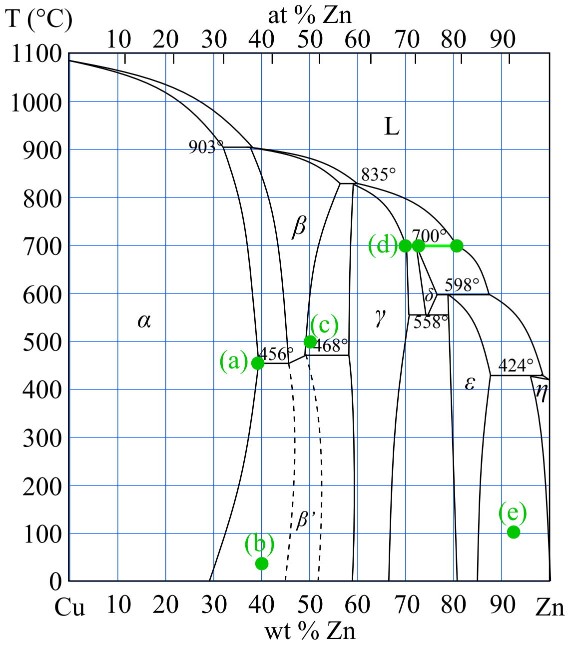
(**c**) (**2 points**) Fill in the atoms comprising the extra-half plane and label with the conventional symbol (⊥) the edge of the extra half-plane that establishes the line direction vector of the edge dislocation shown below.

(**d**) (**3 points**) On the same figure, draw in and label the location of the slip plane on which this edge dislocation glides.



3. Phases and Phase Equilibria (10 points)

Refer to the Cu-Zn binary phase diagram below (from *ASM Metals Handbook*, 8th edition, Vol. 8, (1973), p. 301) to answer the following questions. Recall that "brass" is the common name applied to this alloy.



(a) **(2 points)** What is the maximum concentration of Zn that can be dissolved in α brass?

Ans: 39 wt. % Zn

(b) **(2 points)** Apply the phase rule (F = C-P+1) to calculate the number of degrees of freedom available to a 40 wt% Zn alloy at room temperature.

Ans: F = 2 - 2 + 1 = **1**

(c) **(2 points)** What phase(s) is (are) in equilibrium when β brass (50:50 composition) is held at 500°C.

Ans: $\beta + \gamma$

(d) **(2 points)** Write the reaction that occurs on cooling through the 700°C peritectic isotherm.

Ans: $\gamma + L \rightarrow \delta$

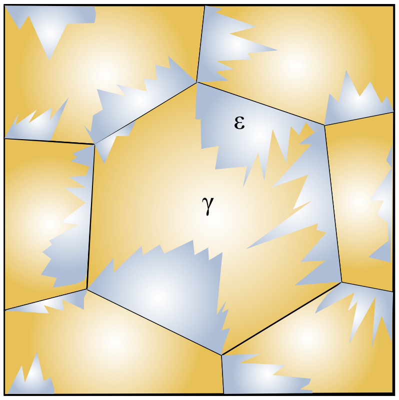
(e) **(2 points)** Both the ε and η phases of brass have hexagonal crystal structures. What composition would yield equal weight fractions of the these two phases in equilibrium at 100°C?

Ans: 92.5 wt % Zn

4. Phases and Phase Equilibria (10 points)

These questions refer to the same Cu-Zn binary phase diagram from Problem 3.

(a) **(5 points)** Sketch the microstructure resulting when a 70 wt% Zn alloy with initially large γ grains at 550°C, as shown below, is cooled slowly to room temperature. Label all phases.

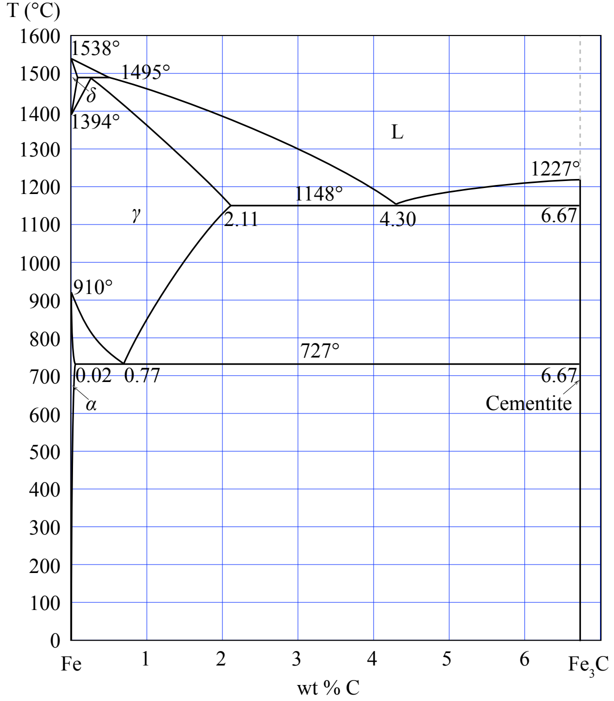


Slow cooling will result in grain boundary precipitation of the ε phase (volume fraction ≈ 25%) within the γ grains (volume fraction ≈ 75%)..

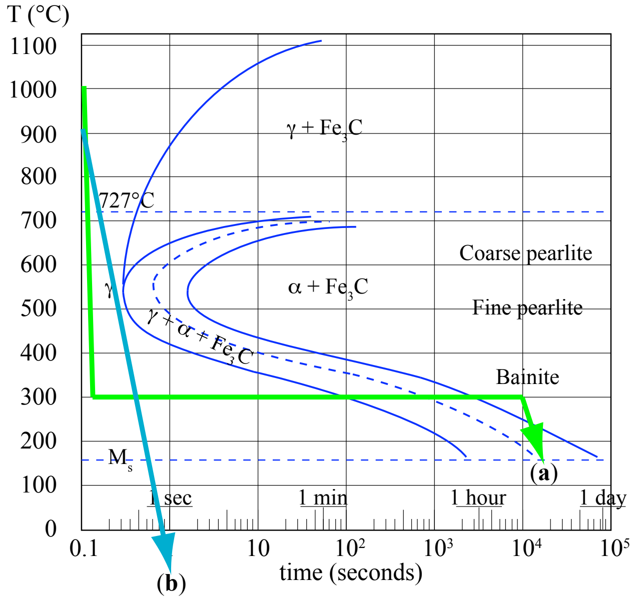
(b) **(5 points)** The eutectoid composition at 558°C is 74.1 wt % Zn. Sketch the microstructure resulting when an alloy of this composition, showing a δ phase morphology at 560°C as shown below, is cooled slowly to room temperature. Label all phases.

At the eutectoid isotherm, all of the δ phase will decompose to the $\varepsilon + \gamma$ in a lamellar constituent, in volume fractions of 40% ε and 60% γ.

5. Kinetics (10 points)
The following phase diagram is from the *ASM Metals Handbook*, 8th edition, Vol. 8, (1973).



(**a**) (**5 points**) The following TTT diagram describes the isothermal kinetics of a 1020 steel. Show directly on the plot a thermal treatment that begins with 100% austenite, and ends with 100% bainite.



(**b**) (**5 points**) Will a quench rate of 1000°C/sec convert a sample with 100% austenite to 100% martensite? Show why or why not on the same TTT diagram above.

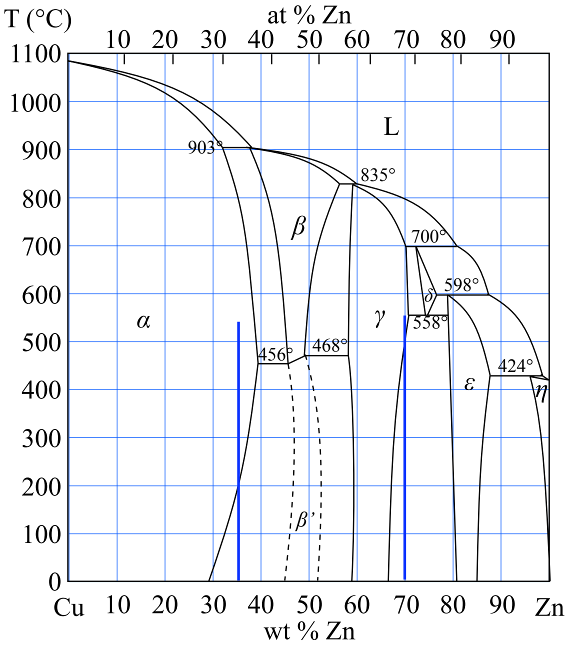
Ans: YES, beginning at 900°C as shown.

6. Kinetics (10 points)
Mark ☒ the ballot box corresponding to the best answer. Two (+**2**) points for correct answers, **-1** if wrong, **0** if blank.

(**a**) The temperature at which a heavily cold worked Cu alloy recrystallizes
☒ decreases as the amount of cold work increases
☐ decreases as grain size increases
☐ both

(**b**) The driving force for grain growth during annealing is
☐ reduction in strain energy
☒ reduction in surface energy
☐ both

(**c**) When metallic alloys are quenched following a homogenization treatment in a single phase region of the phase diagram
☐ a supersaturated solution solution results
☐ the alloy is ready for aging
☒ both



(**d**) Brass can be precipitation hardened if it has the following composition
☐ 35 wt% Zn
☐ 70 wt% Zn
☒ both (see phase diagram above: both can be solutionized as single phase solid solutions, then quenched & aged)

(**e**) Glass ceramics are aged to
☐ relieve internal stress in the glass
☒ precipitate a crystalline phase
☐ both

7. Metallic Alloys (10 points)

Temper	Definition
H1	Strain-hardened
H2	Strain-hardened, partially annealed
T3	Solution-treated, cold-worked, naturally aged
T6	Solution-treated, artificially aged
T9	Solution-treated, artificially-aged, cold worked

The above table is a partial list of the "temper designations" for aluminum alloys specified by the Aluminum Association and published in the *ASM Metals Handbook*, 9th edition, Volume 2 (1979). Recognizing that the specified treatments appearing in the "definition" column occur *in sequence*, and *in the order given*, rank the various temper treatments in order of highest strength to lowest strength.

1. T9
2. T3
3. T6
4. H1
5. H2

Reasoning: In general, the combination of work-hardening *and* precipitation hardening gives the highest overall strength. The T3 temper designation is the one given to aircraft rivets, as described in lecture. Strain hardening alone can be considerable, but if an alloy was designed to be precipitation-hardened (by choice of suitable alloying additions in appropriate amounts), it is expected that an aging treatment can also be designed to maximize strength without the damage of cold work. Those alloys for which the *only* available strengthening option is strain hardening would be treated to earn an H designation, with a judicious amount of cold-work to avoid non-uniform stress distributions that might lead to cracking and/or brittle fracture. Annealing of course softens a material, putting it at the bottom of the list.

8. Metallic Alloys (10 points)

Strengthened by	Weakened by
	Porosity (casting)
Cold working	Annealing
Alloying	Welding
Phase Transformations	Phase Transformations

The above table lists some of the general effects of "processing" of metals and alloys on their mechanical strength. For example, an alloy used in the "as-cast" condition is generally weaker due to the porosity that occurs because of air entrapment during solidification from the liquid phase. Similarly, welding is listed as a cause of "weakening," due to the fact that the local application of heat needed to weld alloys causes significant atomic transport, including some in the liquid phase.

Explain why "phase transformations" is listed in both columns.

Answer: The phase transformations in the "strengthen" column are those that cause *precipitation hardening*. Such transformations result from carefully controlled thermal treatments, beginning with homogenization in a single phase field, followed by rapid quenching to generate a supersaturated solid solution, finishing with an aging treatment to produce a fine dispersion of second phase particles that impede dislocation motion.

The phase transformations in the "weaken" column are those that are not carefully controlled, such as slow cooling from the homogenization temperature, which usually results in a detrimental distribution of second phase particles occurring exclusively at grain boundaries. The grain interiors are therefore made much less resistant to dislocation motion because they have no precipitate particles to serve as obstacles, and many fewer solute atoms that also serve as impediments to dislocation motion (stronger metallic bonding). When such a material is deformed, dislocations move freely through the grains, sometimes with even *lower* strength than the solution solution would have shown.

9. Ceramics and Glasses (10 points)

An important family of "magnetic" ceramics is based upon the spinel ($MgAl_2O_4$) structure. Spinel is formed from an fcc Bravais lattice and a basis of fourteen (14) ions per lattice point: 2 Mg^{2+}, 4 Al^{3+} and 8 O^{2-}. The magnesium ions are tetrahedrally coordinated by four oxygen ions, while the aluminum ions are octahedrally coordinated by six oxygen ions. Note that both the motif and the chemical formula preserve charge neutrality.

However, the magnetic (known as "ferrimagnetic") version of this structure is called an "inverse spinel," in which the octahedral sites are occupied by the divalent ions and one-half of the trivalent ions, while the remaining trivalent ions are in the tetrahedral sites.

One example of the ferrimagnetic ceramics is magnetite, the naturally occurring "lodestone" that was used to make the original compass. It is also found in meteorites. This could be the reason why, in Fox's hit series *The X-Files*, FBI investigators observed that magnetite could disrupt alien life forms, often causing their death or destruction (?).

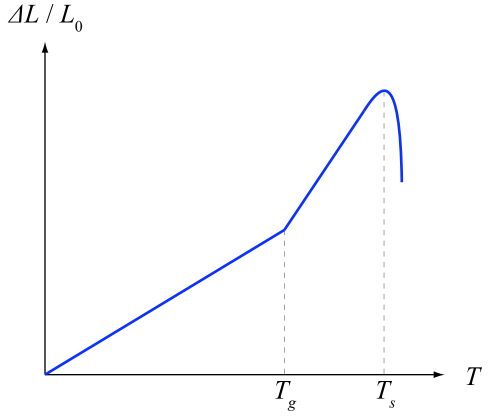
Magnetite is an inverse spinel, yet its chemical formula is Fe_3O_4. Explain.

Answer: The apparent anomaly here is charge balance. If you count up the number of negative charges on the eight (8) O^{2-} ions (= -16) and compare that number with the number of positive charges on six (6) Fe^{2+} ions (= +12), you arrive at a conundrum. However, taking a clue from the opening paragraph above, a spinel consists of both divalent and trivalent cations in the correct ratio (2 of the divalent species and 4 of the trivalent species (= +16) to achieve charge neutrality. So, if the chemical formula of magnetite is correct, its charge distribution must be reconciled. And the way to do that is to give Fe a multivalent character. Assume that it can be either divalent or trivalent.

The answer then is that there are must be two (2) Fe^{2+} ions and four (4) Fe^{3+} ions in this inverse spinel. You can think of the chemical formula in the same format as that for the original spinel, $MgAl_2O_4$, which would be expressed as $FeFe_2O_4$, but the more efficient form is Fe_3O_4.

10. Ceramics and Glasses (10 points)

The following plot shows the thermal expansion behavior typical of a glass. Note that strain is plotted on the vertical axis, with temperature increasing to the right on the horizontal axis. At the softening temperature (T_s), the glass is unable to support its own weight and flows freely, invalidating the thermal expansion data.



During the processing of safety glass for windows, a treatment is used to place the surface of the glass in residual compression, so that it will not be as susceptible to fine surface cracks. In one of these treatments, the glass is first equilibrated above its glass transition temperature (T_g). Next it is subjected to cold air blast on both sides, a "surface quench," to form a rigid but thin "skin" on both surfaces. The skin is cool enough to remain below the glass transition temperature while the interior of the glass is still above T_g. The glass is then allowed to cool slowly and uniformly to room temperature.

Explain how this treatment causes residual surface compression.

Answer: The schematic at right shows how the stress distribution varies with each thermal treatment. The residual surface compression comes during the final stages of cooling, when the larger interior mass of glass contracts, pulling the surface skin into compression.