Department of Materials Science and Engineering
Massachusetts Institute of Technology
3.14 Physical Metallurgy – Fall 2009

Exam II

## Wednesday, December 2, 2009

The Rules:

1) No calculators allowed

2) One hand written 3x5 index card may be prepared as a crutch, and you may also have the cards you made for the last exam.

3) Complete 5 out of the 6 problems. If you do more than 5 problems, I will grade the first 5 that are not crossed out.

4) Make sure that you READ THE QUESTIONS CAREFULLY

5) Supplementary materials are attached to the end of the test (eqns., etc.)

6) WRITE YOUR NAME HERE:

Problem #1: Steel of Mystery

Take a gander at the TTT diagram shown here. This diagram is for an Fe-C alloy, but which one?

875°C

727°C
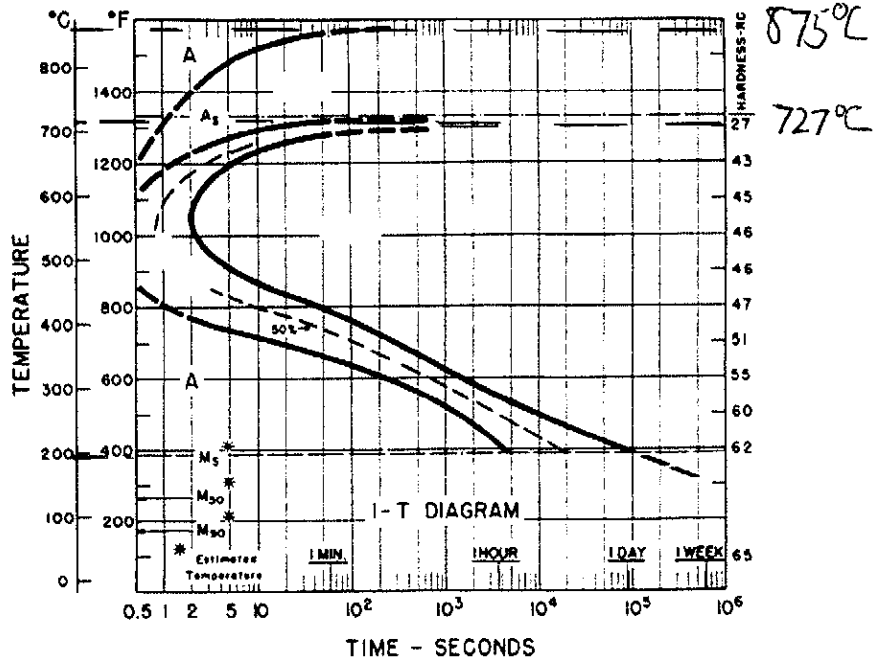
Part A: Based on the equilibrium transformation curves, you should be able to narrow down the possibilities to just two plausible compositions for this alloy. Identify them and explain your reasoning. (Hint: you may need the information at the end of the exam).

③ There is a proeutectic transus at about 875°C.

From the phase diagram, we must be at either ~ 0.2 % or 1.1 wt-% C

Part B: Now, figure out which of the two compositions is the correct one. (Hint: the equilibrium transformations only narrowed the choices. Perhaps the non-equilibrium transformation may help?)

② M_s is at ~200 °C ⤳ from the attached chart: High C-content

⟹ 1.1 wt-% C

Problem #2: A Question That Appears to be About Precipitation Strengthening, but in Fact is About Everything But Precipitation Strengthening

The diagram at the right shows an aging curve for a binary alloy; it shows the strength increase as precipitates are formed, followed by the inevitable decline in strength due to overaging.
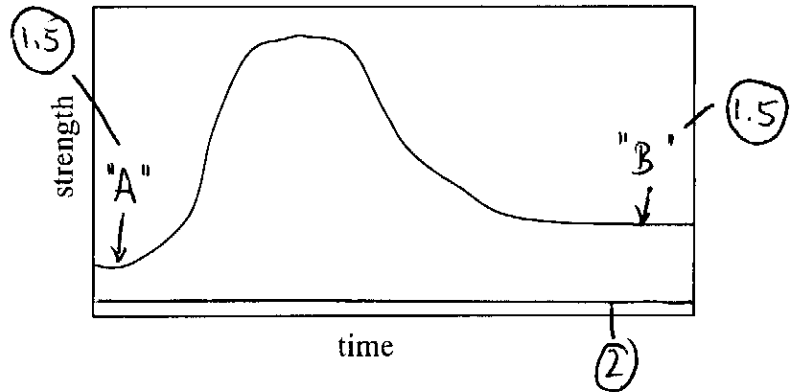
Part A:

On this diagram, draw a horizontal line that represents the strength of the base metal, if it were not alloyed at all. Write a sentence explaining why you chose the location of this line.

At point "A" it is a solid solution, which must be stronger than the base (unalloyed) metal.

The line must be below "A".

Part B:

Observe that at long times of aging, the alloy reaches an asymptotic strength level. This level is above the starting strength of the alloy at the beginning of aging. Explain why, even in the extremely over-aged condition, this material is strengthened as compared to the condition at time zero.

At "B": 2nd phase is large. It still contributes strength by load transfer.

Problem #3: Solid Solution Softie

It seems like we are always trying to make things stronger, doesn't it? Just for a change, let's discuss how we can avoid making something stronger. It may be harder than you think (pun intended; ha).

Consider all the possible binary solid solutions you could make with aluminum; every other element in the periodic table is a possibility. As we discussed in class, most everything we could add in solution will usually lead to strengthening. Using the information provided at the back of the test, identify a few elements that you think will have a negligible or small solid solution strengthening effect in aluminum. Rank these, and be sure to identify the element you think will cause the least strengthening. (For this problem, compare the elements assuming the same amount of each can be put into solution in Al)

We want :   Same size   and   Same shear modulus as Al ①

Al : shear modulus : 26.2 GPa
      size   : 143 nm   } ①
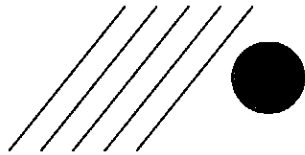
Elements that are at least close to one of these ①

	G in GPa	r in nm
Sb	20.7	.138
Cd	24	.148
Ge	29.6	.139
An	26.0	.144
Ag	30.3	.144
Th	30.8	?
Y	25.5	.181

Ge, An → nearly identical in size and G ①

Ag .144 → 2nd choice

Problem #4: Shearing, Shearing, Shorn

Consider a single precipitate interacting with a dislocation pile-up, as shown.

The applied stress (force) is gradually increased until the particle is sheared by the dislocations. They pass through one at a time, as the strain level is increased. The force required to effect this is shown at the right.
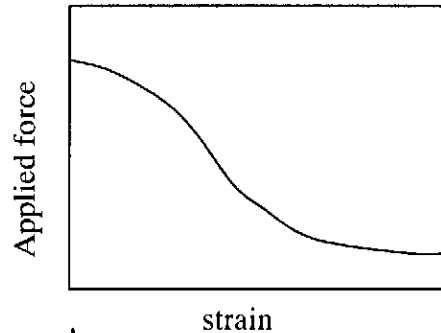
Part A: Explain why the force required to move dislocations drops off considerably with the applied strain.

As ⊥ cut through, the "effective" size decreases.

②

eventually there is nothing left to cut ⤳ less τ required for each ⊥
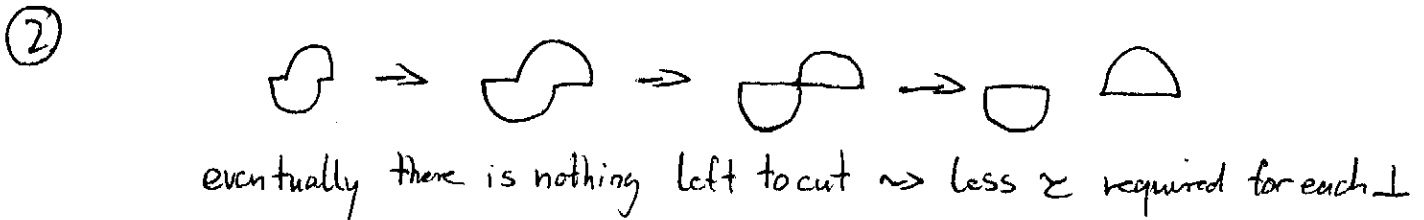
Part B: Explain why the force does not keep dropping at large strains; why is there a plateau?

If all particles are cut to shreds, there is still solid solution like effects on top of regular work hardening, ...

①

Part C: Do you think the precipitate is an ordered intermetallic, or a disordered terminal phase? How would the force curve look if it were the other choice?

Intermetallic would oscillate with each passing ⊥

②

creates APB

⟹ particle above is unordered terminal phase
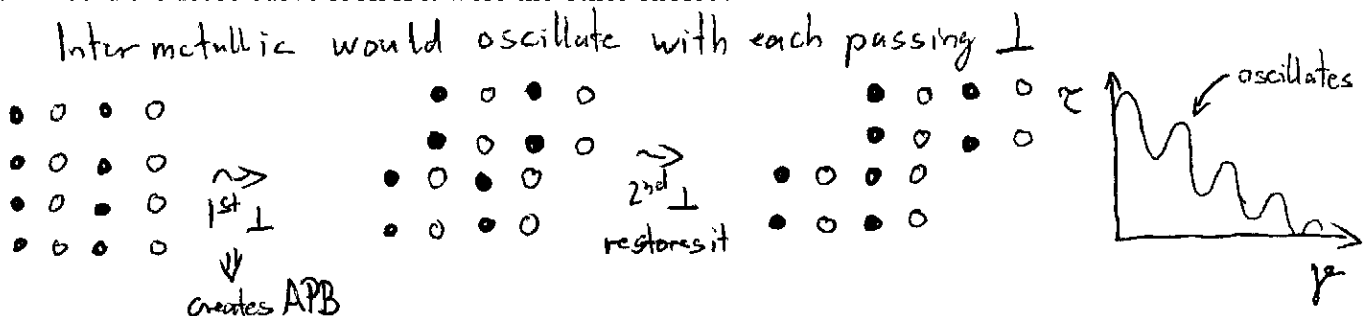
Problem #5: In Which Steel Heat Treatment Schedules Comprising Multiple Steps Appear

In class we discussed the structures of eutectoid steel that form during isothermal treatments, using the TTT diagram here. Pretty much all of the cases we discussed were for a single step treatment. Now, consider a few cases in which we use more than one heat treatment step. For each case, indicate the structures and phases that will be present at the end of the treatment, including their fractions (where possible).
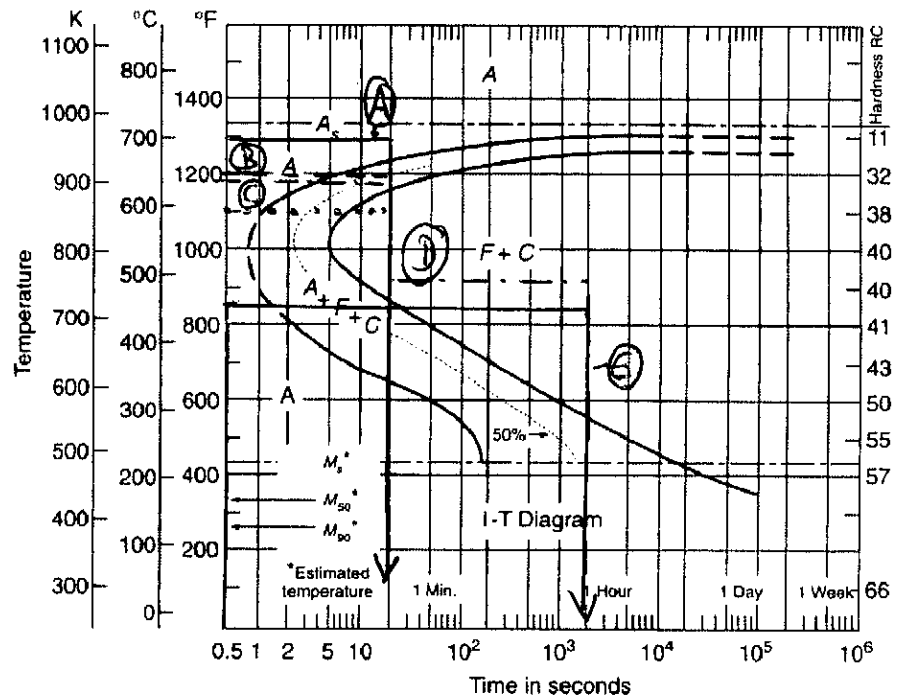
Part A: The steel is rapidly cooled to 700° C, held for 20 seconds, and then rapidly quenched.

① No breech of the start curve ⇒ γ transforms to M

    ⎡ M (with retained γ) ⎤   see Ⓐ —

Part B: The steel is rapidly cooled to 650° C, held for 20 seconds, and then rapidly quenched.

① ~50% transformed to (α + Fe₃C) Perlite, remaining γ ⇒ M

    ⎡ P, M, some retained γ ⎤   see Ⓑ – –

Part C: The steel is rapidly cooled to 600° C, held for 20 seconds, and then rapidly quenched.

fully transforms to Perlite (fine P ' near nose)

    ⎡ P ⎤   See Ⓒ • • •

Part D: The steel is rapidly cooled to 650° C, held for 20 seconds, then cooled to 500° C and held for an hour.

50% Pearlite @ 650°C (coarser)
remainder Bainite @ 500 °C (upper)

    ⎡ 50% P / 50% B ⎤   Se Ⓓ — • —

Part E: The steel is quenched, then rapidly reheated to 450° C and held for 1 hour and quenched again.

M ⇒ Ⓑ (Lower)

    Ⓑ

Problem #6: Caring is Load Sharing

Consider the following five materials, each of which involves a hard and stiff ceramic phase, and a soft and compliant metallic phase. Based on the information given, describe whether you think an upper-bound or a lower-bound estimate would be appropriate to average the elastic moduli of the two phases. Write one sentence of explanation for each case.

Part A: The ceramic is in the form of particles, comprises about 15% of the volume of the material, and is well dispersed.

① Low V_f ⟹ disconnected particles ⟹ dominated by the metal

lower bound

Part B: The ceramic is again in the form of particles that are well dispersed in the metal, but have a volume fraction of 60%

① high V_f ⟹ probably percolatry, dominated by ceramic

upper bound

Part C: The ceramic evolves by phase separating from the metal in a eutectoid reaction, and comprises about 50% of the volume of the material.

① eutectic ⟹ aligned / well connected phases

upper bound

Part D: Ceramic particles are pressed together in air to form a powder compact, and then molten metal is squeezed into the compact and solidified.

① ceramic is by processing, fully connected + percolating

upper bound

Part E: Chopped ceramic fibers with a high aspect ratio are dispersed into the metal; the fibers have a volume fraction of 20%.

① Long fibers percolate easily ⟹ probably above the threshold

upper bound

Helpful (?) Bonus Information
<u>Stress field around an edge dislocation:</u>

$$\sigma_{xx} \propto \frac{y(3x^2 + y^2)}{(x^2 + y^2)^2}$$

$$\sigma_{yy} \propto \frac{y(x^2 - y^2)}{(x^2 + y^2)^2}$$

$$\sigma_{xy} \propto \frac{x(x^2 - y^2)}{(x^2 + y^2)^2}$$

all other σ components are $= 0$.
<u>Stress field around a screw dislocation:</u>

$$\sigma_{rz} \propto \frac{1}{r}$$

all other σ components are $= 0$, and note that $r^2 = x^2 + y^2$
Forces between dislocations:
Parallel edge:

$$F_y = \frac{\mu b^2}{2\pi(1-v)} \frac{y(3x^2 + y^2)}{(x^2 + y^2)^2}$$

$$F_x = \frac{\mu b^2}{2\pi(1-v)} \frac{x(x^2 - y^2)}{(x^2 + y^2)^2}$$

Parallel screw:

$$F_r = \frac{\mu b^2}{2\pi r}$$

JMAK Equation:
$f = 1-\exp(-kv^d t^{d+1})$

Orowan bowing strength:
$\Delta\tau = \mu b v_f / r$

Strength gain from APB creation in a precipitate:
$\Delta\tau = (\pi\gamma_{APB}v_f)/(2b)$

Strength gain from surface area creation; precipitation strengthening:
$\Delta\tau = (\pi\gamma_s v_f)/(b)$

Isostrain analysis: $E_c = E_1 v_1 + E_2 v_2$

Figure showing radii of atoms and ions removed due to copyright restrictions.
Please see any chemistry textbook, such as
http://boomeria.org/chemlectures/ch10atomicradii.jpg

Please see Fig. 19.17 in Reed-Hill, Robert E., and
Reza Abbaschian. *Physical Metallurgy Principles*.
Boston, MA: PWS Publishing, 1994.

Table of Young's modulus and shear modulus values for all metals removed due to copyright restrictions.
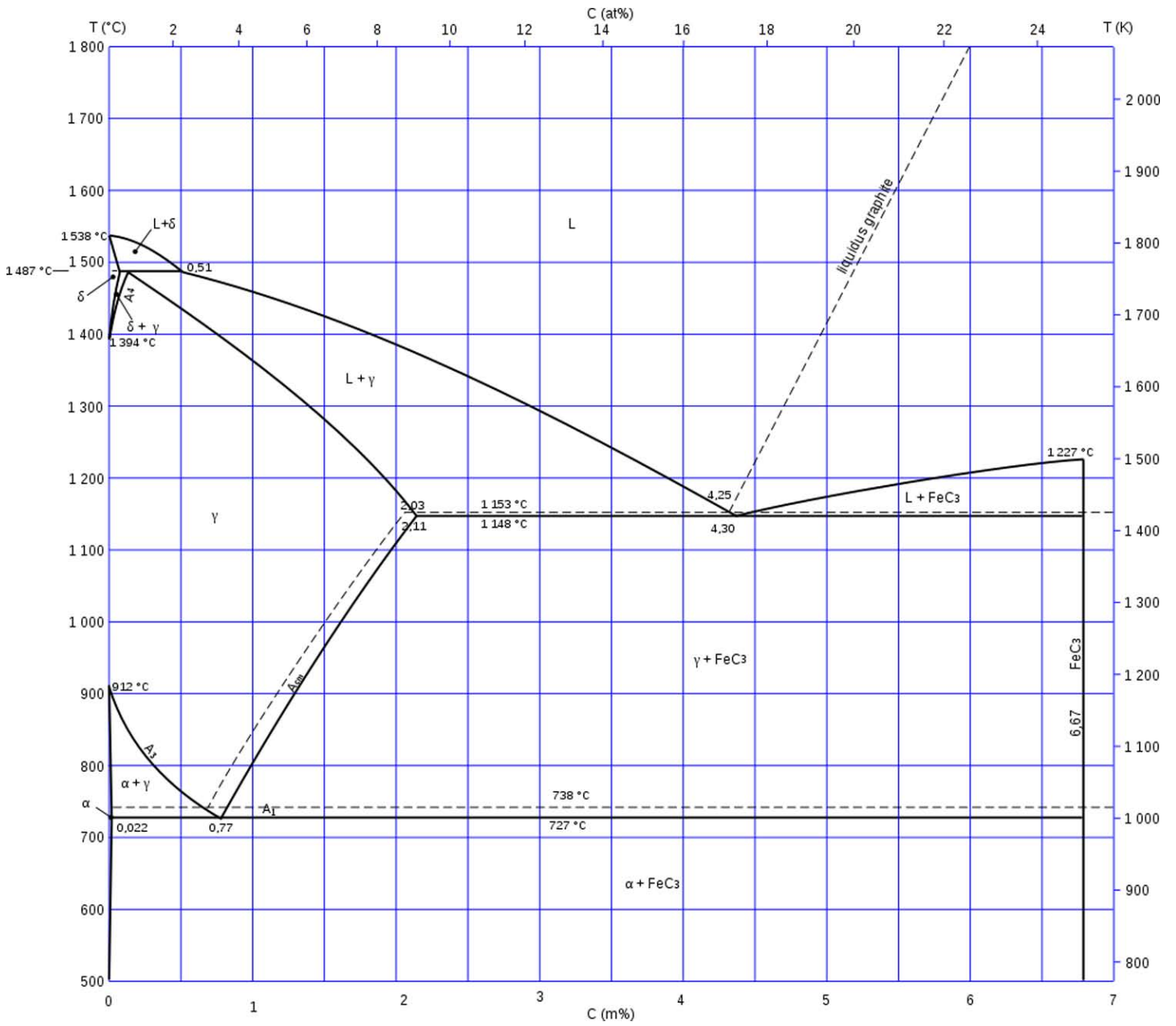
Image from Wikimedia Commons, http://commons.wikimedia.org.

3.40J / 22.71J / 3.14 Physical Metallurgy
Fall 2009