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

Professor R. Gronsky

Fall Semester 2010

Engineering 45

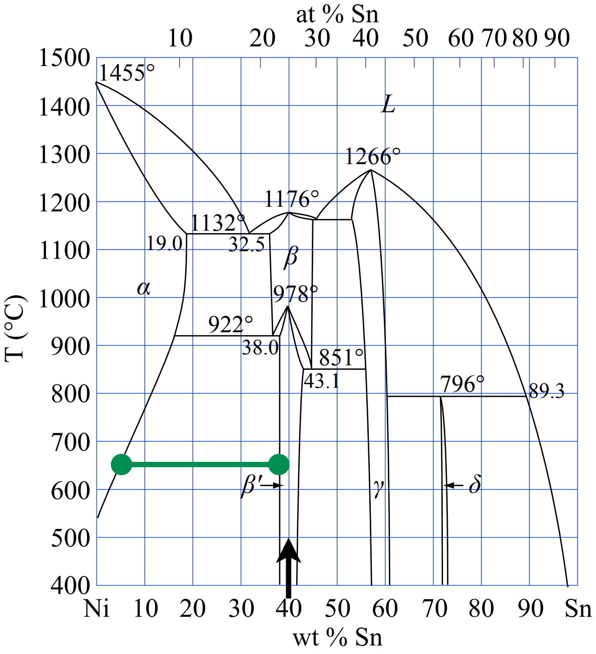
Midterm 02

Solutions

INSTRUCTIONS

PATIENCE	Do not open pages until “START” is announced.
PRUDENCE..............................	Position yourself with *occupied* seats directly in front of you and *vacant* seats to your left / right, when possible, unless instructed by exam proctors.
PROTOCOL..............................	Only *writing instruments / eraser / straightedge* are allowed. Remove all other materials, including books / reference materials / calculators / PDAs / cell phones (disable all sounds) / other electronic devices / headphones / ear buds / hats from your person / workplace.
POLITENESS	Asking and answering questions during the exam are very disruptive and discourteous to your classmates. So there will be *no questions* during the exam. Instead, please include your concerns or alternative interpretations in your written answers.
PROFESSIONALISM	The engineering profession demands strict ethical standards of honesty and integrity. Engineers do not cheat on the job, and there will be **no cheating** on this exam.

1. Phase Diagrams

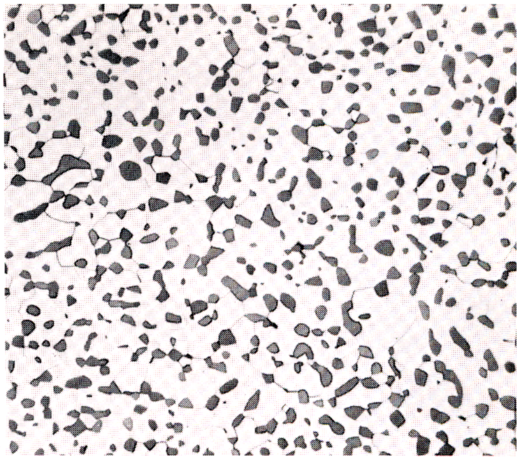


a. The intermetallic compound Ni_3Sn assumes either cubic or hexagonal crystal structures, and when it precipitates in Ni-base alloys, results in significant strengthening, even though Sn melts at 231°C.

What is the *minimum alloy composition* of Sn required to generate precipitates of this strengthening phase for applications at 650°C?

Explain.

At 650°C, a tie line construction shows that the composition of the pure α phase is just under 5 wt% Sn. Consequently, for a Ni-base alloy to precipitate β' phase at this temperature, it must have a **minimum composition of 5 wt% Sn**, with **somewhat more** Sn being ***better***, because higher Sn concentration will increase the density of the precipitate phase, offering more obstacles to dislocation motion.

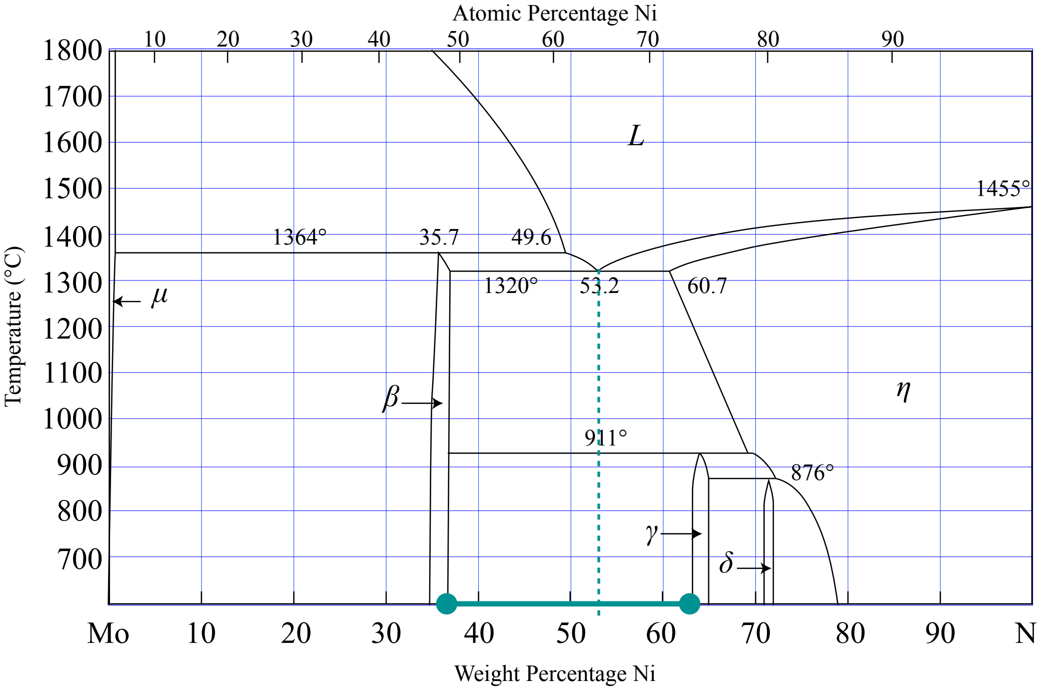


b. A Ni_3Sn precipitation-hardened alloy was implicated in a catastrophic failure after 3 years of service at 650°C, launching a microstructural study that generated the (room temperature) micrograph at right. The prosecuting attorney claimed that the reason for the failure was the "wrong alloy composition," which she stated was "*proven by the micrograph to be exactly 40 wt% Sn*." The defense calls you to the stand as an expert witness. What do you say?

You are entitled to say "**Nonsense**!" At 40 wt%, the microstructure should be single phase β' (phase diagram) but this micrograph clearly shows two phases. Because the alloy was precipitation hardened, the dark phase seen here is the β' phase (lower volume fraction confirmed by tie line) in a matrix of α. Also from the tie line, the composition is closer to 15 wt% Sn. **The reason for failure must be something else**.

1. Phase Diagrams

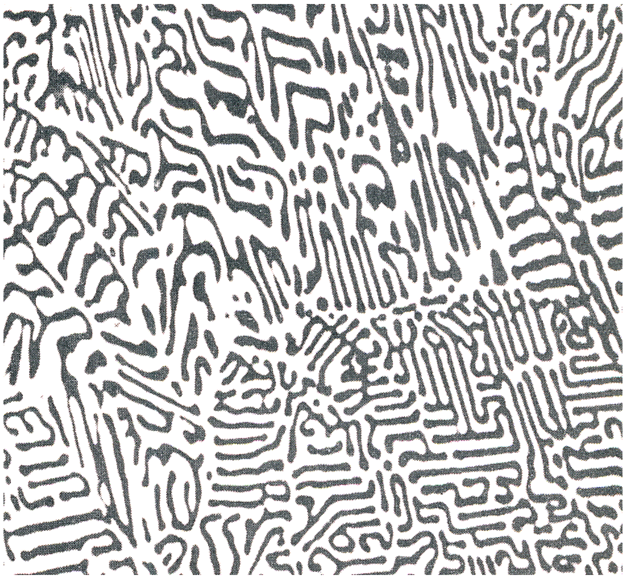
c. Another alloying constituent used in Ni-base alloys is molybdenum, which is favored because of its "extended solid solubility." What specifically is its *limit of solid solubility* in this case? Explain.



The label at the right terminus of the 1320°C eutectic reaction isotherm is the answer, revealing that Ni can dissolve up to a maximum (its "limit of solid solubility") of 100.0 – 60.7 = **39.3 wt. % Mo**.

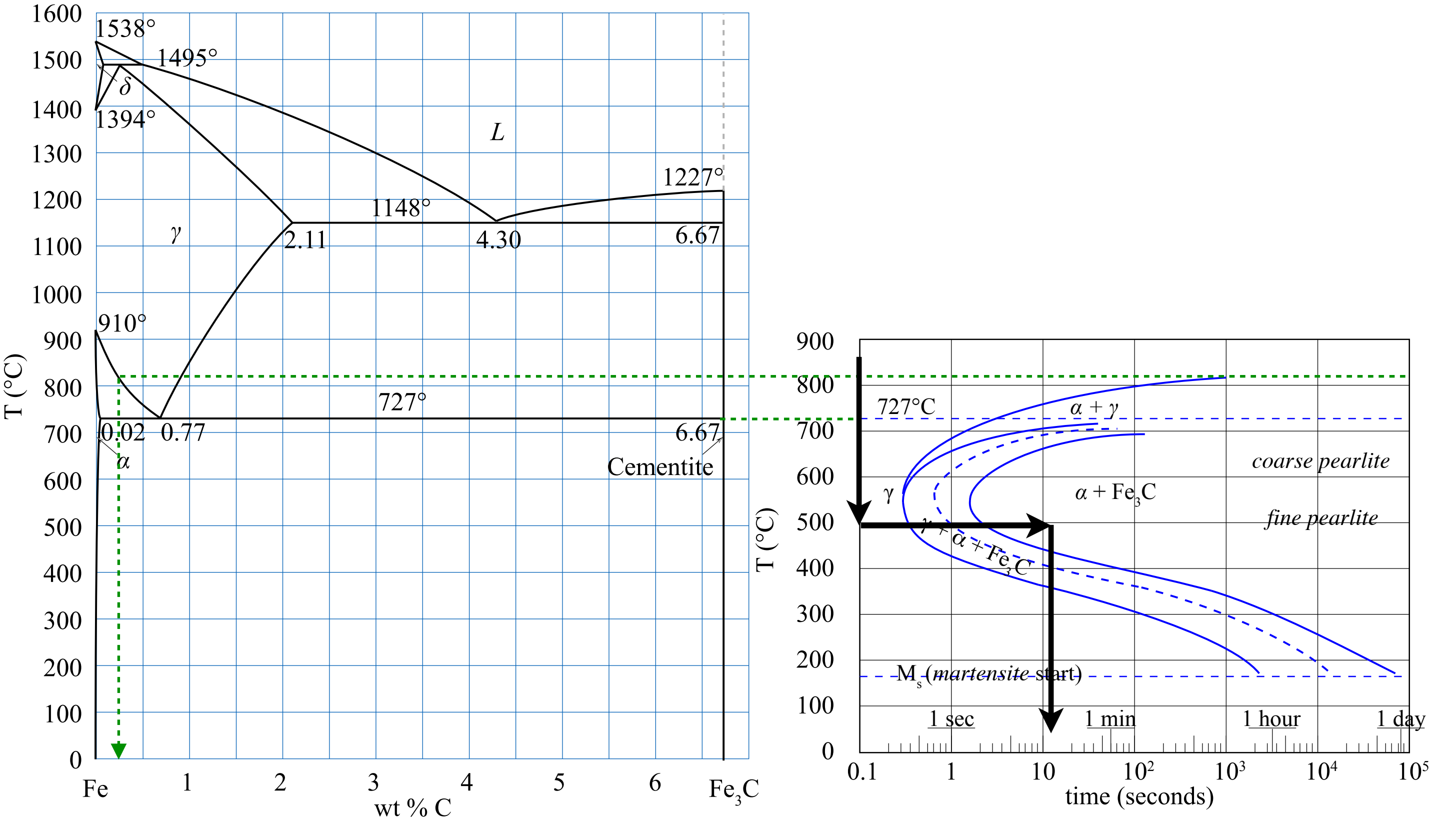
d. One problem with Ni-Mo alloys is their propensity to form *β*, *γ*, or *δ* phases, all of which lead to embrittlement. The microstructure at right was obtained from a polished and etched sample that fractured in a brittle manner at room temperature. What is the overall *composition* of the alloy in this case, and what is the *identity* of both phases (light and dark) seen here?

Explain.



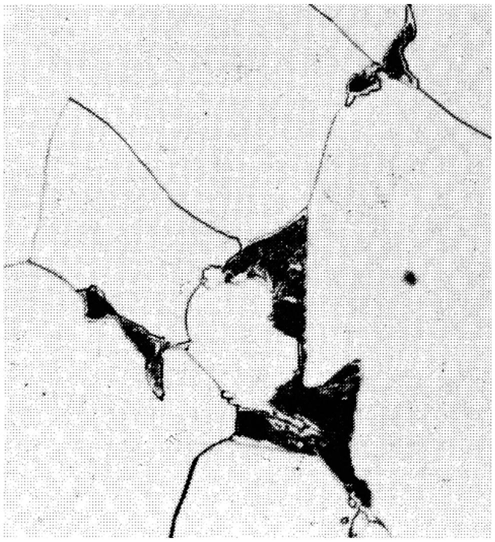
This lamellar microstructure results from cooling through the eutectic point (there are no eutectoids on the diagram), at an alloy composition of exactly **53.2 wt % Ni**. At 911°C, the eutectic product *β* + *η* decomposed by a peritectoid reaction to generate *β* + *γ* phases on the eutectic template (*β* remains, but decreases in size). A tie line reveals that the larger volume fraction phase is *γ*, so the ***γ* phase is light** in color, the ***β* phase is dark** in color.

2. Kinetics in Ferrous Systems



a. What is the *composition* of the plain carbon steel described by the TTT curve above? *Explain*.

The maximum temperature at which pro-eutectoid α phase exists on the TTT plot is traced over to the phase diagram (co-linear eutectoid isotherm at 727°C are the guide), then converted to the appropriate composition, shown here to be **0.25 wt % C**.

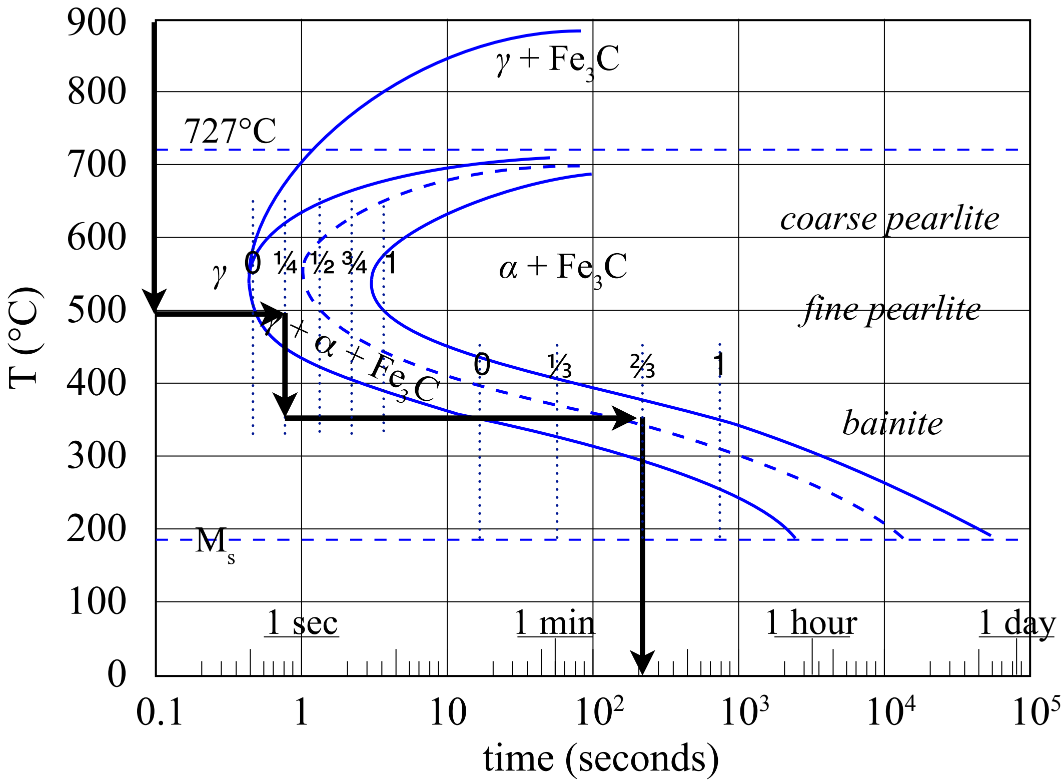


b. What *cooling path* (show directly on the TTT plot) would have been employed to generate the microstructure shown at the right? Explain.

A tie line construction above the eutectoid shows a predominance of proeutectoid α phase, which is the light microconstituent here. The dark microconstituent must therefore be pearlite with a lamellar spacing too **fine** to be seen at this magnification, suggesting the isothermal cooling curve shown above.

2. Kinetics in Ferrous Systems

c. On the TTT curve at right, plot the full trajectory, in isothermal segments, of a heat treatment that converts austenite to a microstructure of 25% martensite, 25% fine pearlite and 50% bainite. Precision is critical here: draw *sharp lines* and clearly *label* the location of all fractional transformations.

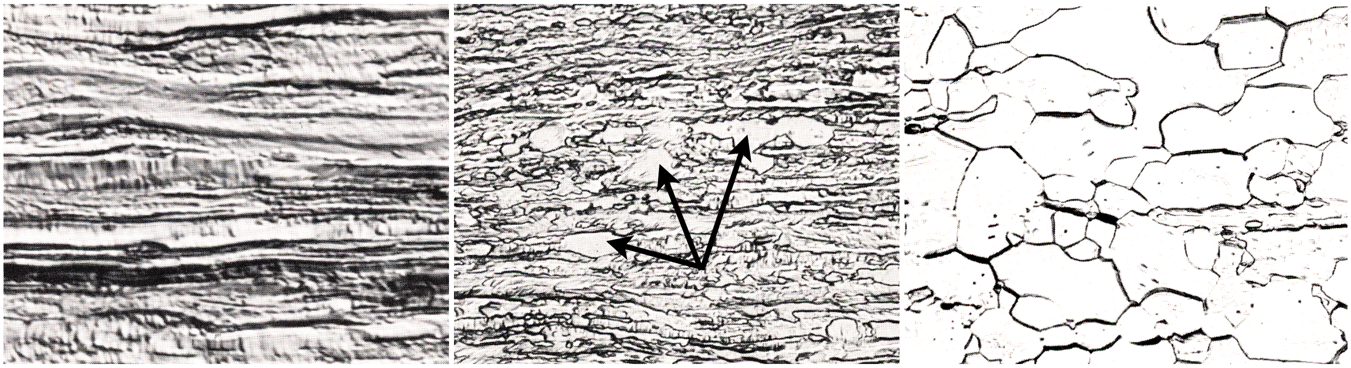


Quench to 500°C; transform ¼ of the austenite to fine pearlite (25%); quench to 350°C; transform ⅔ of remaining austenite to bainite (⅔ of 75% = 50%); quench remaining austenite to martensite (25%).

d. Microstructural examination after your successful heat treatment of the above steel confirms the presence of martensite, pearlite and bainite, but your metallographic technician (a Stanford dropout) is surprised to find a fourth microconstituent as well. Without looking at the microstructure, you patiently describe to your technician *what* it looks likes, *where* it appears in the microstructure, *when* it formed during your heat treatment, and *what* it is named. Explain what you said to your technician.

Because you paid attention to the TTT plot showing a proeutectoid $Fe_3C + \gamma$ phase field, your comments might have gone something like this…
"No surprise; it's just what I expected. I'm sure you saw a **blocky** morphology lining the **prior austenite grain boundaries** because it formed **first**, during cooling through the solvus on the way to the eutectoid reaction isotherm. That familiar phase is the **proeutectoid cementite**."

3. Kinetics in Non-ferrous Systems



a. The three micrographs above comprise a time sequence during the annealing of a cold-worked tungsten wire used as a heating filament. At left, $t = 0$ ("as-drawn"), at center, $t = 15$ min., and at right, $t = 2$ hrs. What is the *driving force* causing the microstructural changes in the second and third frames? Explain.

The center frame shows several recrystallized grains; the driving force for which is the **reduction in strain energy** after cold working by wire drawing. New dislocation-free grains nucleate and replace the deformed grains with high dislocation density present in the first ($t = 0$) frame.

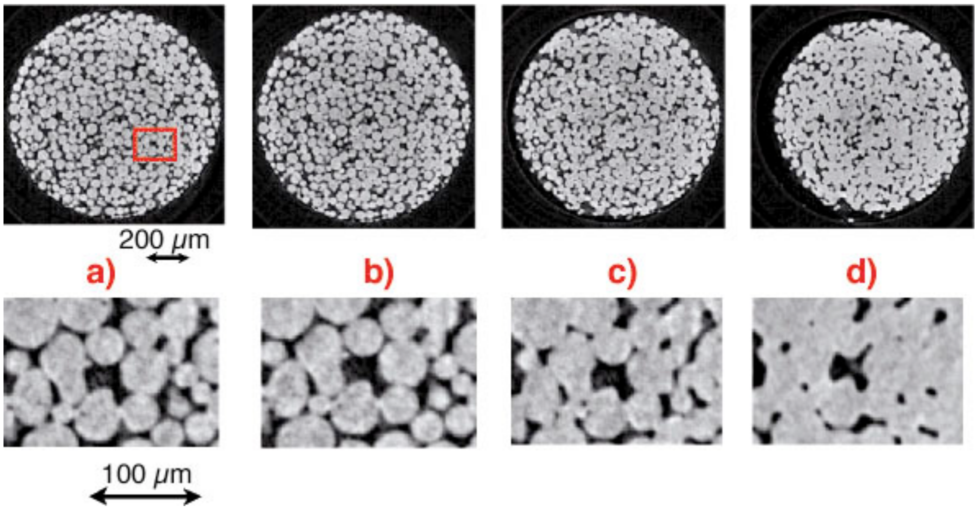
The last frame shows considerable grain growth; the driving force for which is the **reduction in surface energy** after recrystallization. Large grains grow at the expense of small ones to reduce the overall grain boundary area.

b. How are the kinetics of the microstructural transformations exhibited above influenced by *temperature*? Explain, citing the limits on the *range* of temperatures available for controlling kinetics in both frames 2 and 3.

The kinetics of both recrystallization (frame 2) and grain growth (frame 3) are enhanced by **diffusion**, a thermally-activated process. At temperatures below ⅓ of the "melting" or solidus temperature, diffusion is **inhibited**; kinetics can be slowed substantially or even stopped. As the temperature increases, diffusion is **favored**, the rate of both recrystallization and grain growth increases, limited only by the appearance of liquid phase at the upper end of the temperature range, when $T = T_M$, the melting or solidus temperature. It is safe to assume that the above sequence occurred at a temperature between ⅓ and ½ of T_M.

3. Kinetics in Non-ferrous Systems

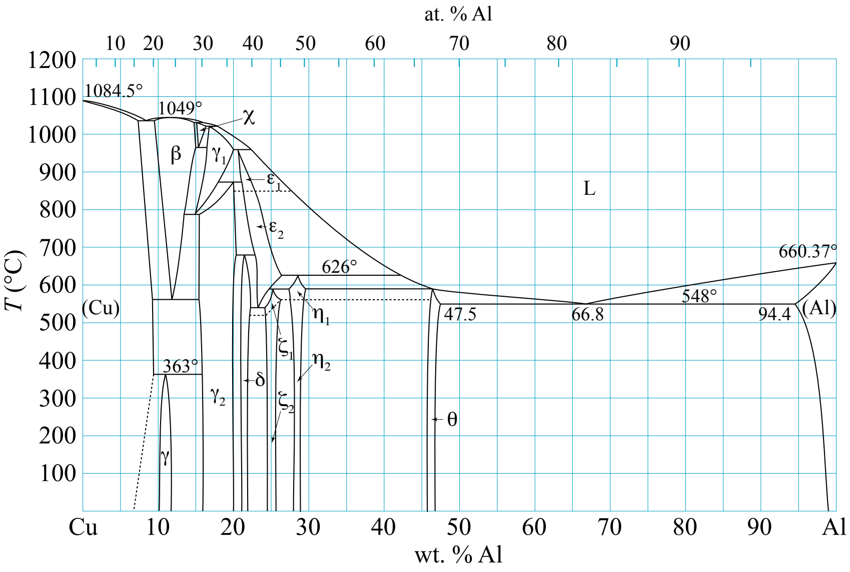
c. The four sets of images at right comprise a time sequence in the sintering of TiO_2 powder particles. What is required to generate a final sintered product with *full* density? Explain.



Full density requires: **high pressure** to increase contact between particles; **high temperature** to enhance diffusion kinetics; **long times** in the sintering furnace to complete the densification process, and **grain refiners** (chemical agents that "pin" grain boundaries to restrict rapid grain growth) if needed to retain pores at grain boundaries so they may be closed by grain boundary diffusion.

d. Explain the significance of the "quench and age" treatment needed to induce precipitation hardening in an Al-Cu alloy system.

What purpose is served by both the "quench" component and the "age" component of the treatment? Explain, citing the kinetics of both.

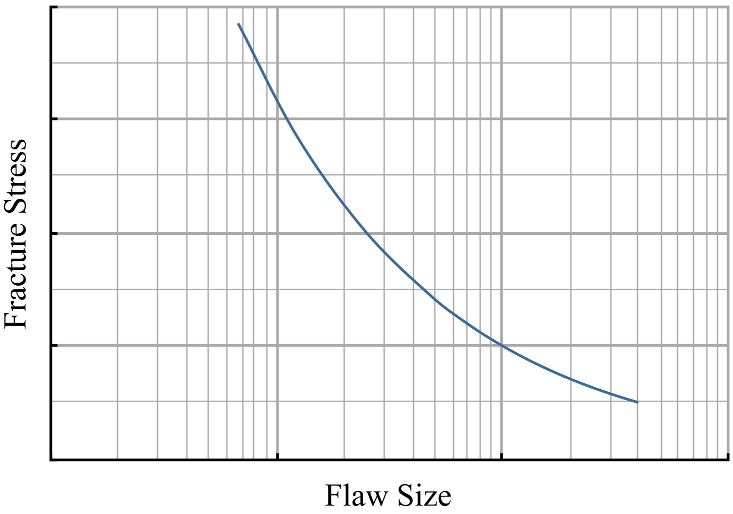


An alloy with no more than 4.6 wt% Cu is first heated to the single phase (Al) field. Next, a **quench** (rapid cooling to minimize thermal activation on the way down) retains the Cu in supersaturated solid solution. The alloy is then **aged** at low temperature to favor a high nucleation rate and minimum growth, producing a high density of fine precipitates serving as barriers to dislocation motion.

4. Failure of Engineering Materials

a. The study of materials with "pre-existing flaws" is traditionally known as the field of "fracture mechanics." It acknowledges that engineering materials are imperfect, and that those imperfections affect properties in a significant way. One prominent subject of fracture mechanics is called "fracture toughness," employing a "stress intensity factor" (K_{IC}) to relate fracture stress (σ_f) and the depth of a surface crack (a).

$$\sigma_f = \frac{K_{IC}}{\sqrt{\pi}} \left(\frac{1}{\sqrt{a}} \right)$$



For metallic alloys, tabulated values of K_{IC} often show a range, such as 23 to 45 MPa√m for aluminum alloys. Explain how *grain size* might affect K_{IC} in a metallic alloy.

Metallic alloys deform by dislocation motion. Large grains offer fewer barriers to dislocation motion, enabling metallic alloys to deform more readily in the vicinity of the crack tip, blunting the crack, and raising the amount of stress that can be accommodated before fracture.

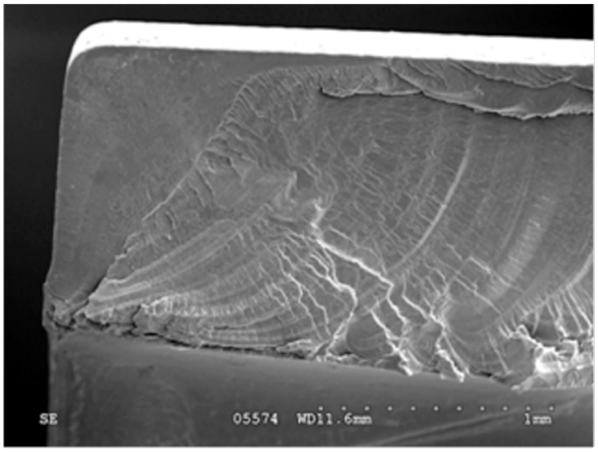
So **larger grains are associated with a larger K_{IC}.** (metallic alloys only)

b. Ceramic materials don't exhibit a "yield" stress. They fail by "fast" fracture in a brittle manner, at correspondingly low values of K_{IC}. Yet some ceramic materials are said to be "toughened" by a "microcracking" mechanism. Explain how *grain size* might affect K_{IC} in a ceramic that undergoes microcrack toughening.

Ceramics do not deform by dislocation motion, except at unrealistically high temperatures (too high for normal engineering applications), but can accommodate some stress by the generation of microcracks before failure. Small grains enable more microcracks along weaker grain boundaries that can dissipate fracture by crack deflection and effective crack blunting.

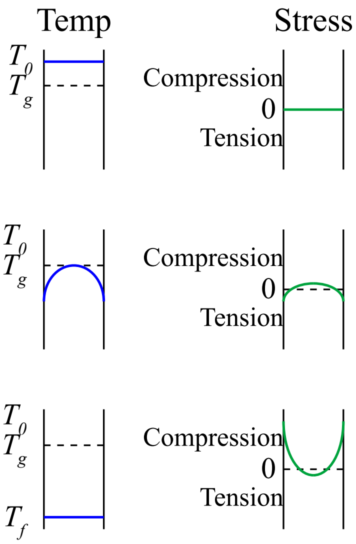
So **smaller grains are associated with a larger K_{IC}.** (microcracking ceramics)

4. Failure of Engineering Materials



c. The scanning electron micrograph at right shows characteristic "beachmarks" or "clam shell" lines on the surface of a hinge component that failed in fatigue at several thousand cycles under a stress less than one-third of its ultimate tensile stress. It was later found that the fatigue strength of a hinge increased if it was *cold-worked* before placing it in service. How would you explain this tendency, based upon a dislocation model?

A fatigue crack initiates where dislocations intersect the free surface (at a location indicated by back-tracing beachmarks on a fracture surface to their origin). To initiate a surface crack, dislocation motion is required. Cold work reduces dislocation motion by adding barriers (more dislocations) to that motion. Consequently cold working **increases** fatigue strength by **inhibiting crack initiation**.

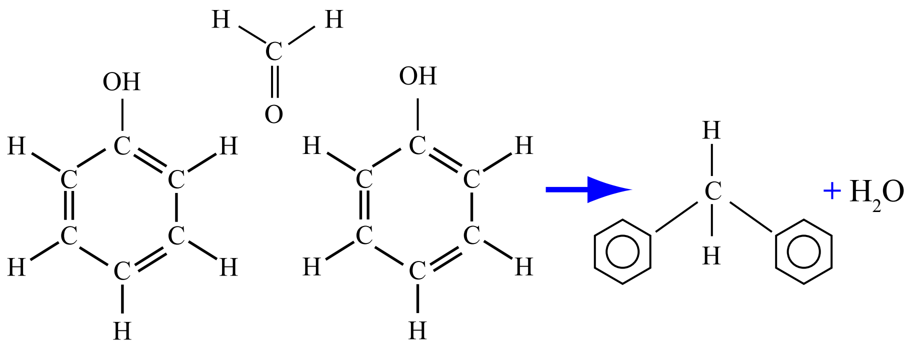


d. The "tempering" of glass requires a three step treatment: homogenization at a temperature just above the glass transition temperature T_g; cooling of the surface to below T_g; and finally, slow uniform cooling to room temperature, as illustrated with corresponding stress states at right.
What happens if, in an attempt to increase production, the second step is initiated earlier, when the glass is at a temperature $T >> T_g$? Explain.

When the glass is too hot, its surface cannot be cooled below T_g during the surface "quench." Consequently the surface will **not** be drawn into temporary tension, but will readily deform to **relax all stress gradients**. As the glass cools slowly (uniformly) to room temperature, all of it passes through T_g at the same time, again relaxing all stress gradients. The surface will NOT be under compression and the interior will NOT be under tension; the result is **NO residual stress**.

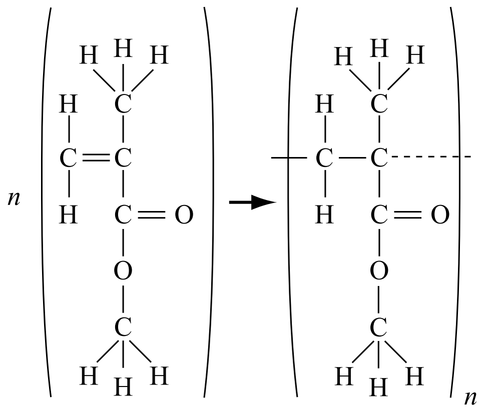
5. Polymers

a. The phenol molecule has a six-membered ring of carbon atoms, rendering it a "polyfunctional" mer. As shown in the schematic at right, it can accept connections to other carbon atoms at any one of six sites when generating a polyphenolformaldehyde network by condensation polymerization. However it is found experimentally that phenol is only "trifunctional." Explain.



There is simply **not enough space** for all six carbons on the phenol ring to simultaneously connect to other phenols. Connecting at **every other carbon** (on average) is possible however, which explains its "trifunctional" nature. This inhibition of polymer functionality due to size of the attachment groups is known as "steric hindrance" in the scientific literature, to distinguish it from electronic (orbital overlap, dipole interactions) and other effects that influence packing density in polymers.

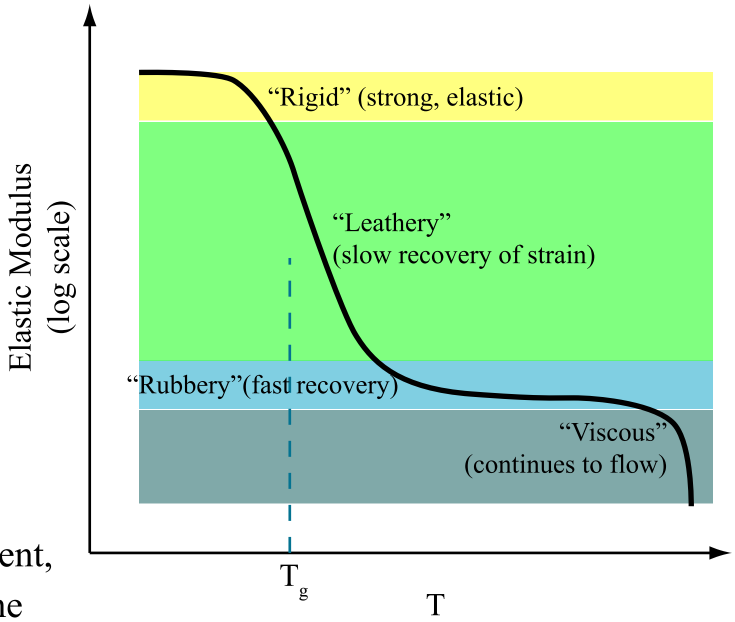
b. The methacrylate molecule is shown below. Is polymethylmethacrylate a candidate for chain growth or step growth? Explain with a sketch showing its functionality.



The **double carbon bond** is the clue, as with all linear polymers. Initiation can cause a bifunctional mer, leading to **chain growth** by addition polymerization up to a degree of polymerization *n,* as indicated in the sketch above.

5. Polymers

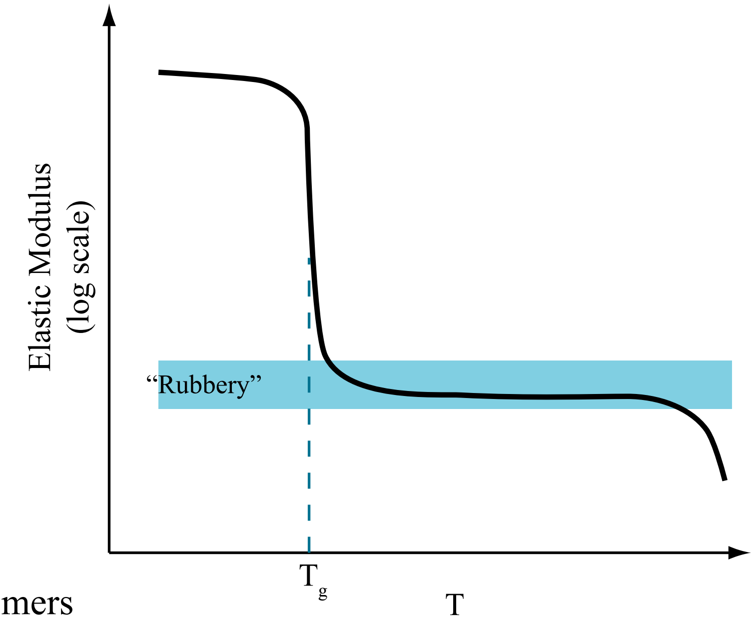
c. How does microstructure affect the viscoelastic response of polymers? Explain, citing the influence of cross-linking and branching in particular.



Cross-linking joins mers from adjacent backbone chains by covalent bonding, **preventing** any lateral sliding of those chains past one another, increasing rigidity and elevating the modulus at all temperatures.

Branching **inhibits**, but does not prevent, the sliding of backbone chains past one another. It causes a modest increase in modulus at all temperatures and slows the recovery of strain above T_g.

d. Elastomers are most often thermosetting polymers, like polyisoprene, best known in its vulcanized form. However more attractive modern elastomers mimic the microstructure of glass ceramics in reverse, with relatively strong thermoplastic domains embedded in a relatively soft crystalline thermoplastic matrix. What makes these thermoplastic elastomers so attractive, from an engineering perspective? Explain.



Thermoplastic (soft at high T) elastomers offer at least two attractive advantages in engineering applications: they are **readily formed into complex shapes** by flow or injection molding at high temperatures, and they are **recyclable**.