SOLUTIONS

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

Professor R. Gronsky　　Fall Semester 2013

Engineering 45

Midterm 02

This is a 50 minute examination with 5 equally weighted problems.

INSTRUCTIONS

①..........Do not open these pages until "START" is announced.

②..........Print your name clearly in the box above.

③..........Remember your Honor Code!

④..........Silence and stow all cellphones and electronic devices.

⑤..........Only *writing instruments / eraser / straightedge* are allowed.

⑥..........There are *no questions allowed* (too disruptive) during the exam.

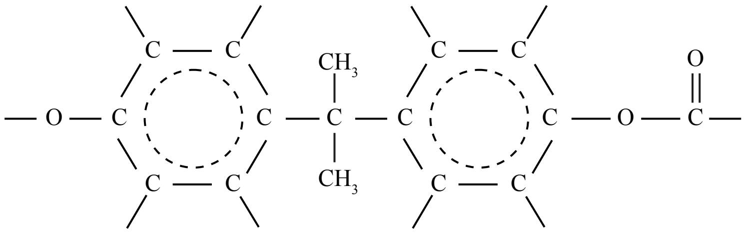
Worksheet

(There will be no points awarded for work shown on this page. Enter your answers on the following pages in the space provided.)

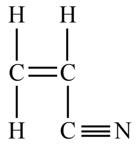
$$J_x = -D\frac{\partial C}{\partial x} \qquad \frac{dQ}{dT} = -kA\frac{dT}{dx} \qquad \sigma_m = 2\pi\sqrt{\left[\frac{c}{\rho}\right]}$$

$$\frac{\partial C_x}{\partial t} = D\frac{\partial^2 C}{\partial x^2} \qquad \alpha = \frac{1}{l}\frac{dl}{dT} \qquad MOR = \frac{3FL}{2bh^2}$$

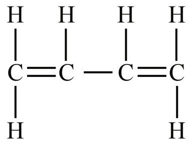
$$D = D_0 e^{-Q/RT} \qquad \frac{N_v}{N} = Ce^{-E_v/kT} \qquad K_{IC} = Y\sigma_f\sqrt{\pi a}$$



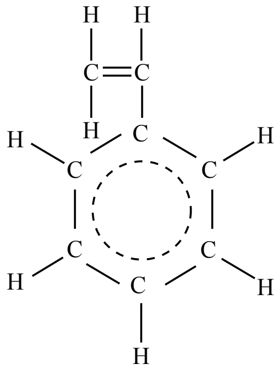
Polycarbonate



Acrylonitrile (graft)



Butadiene (chain)



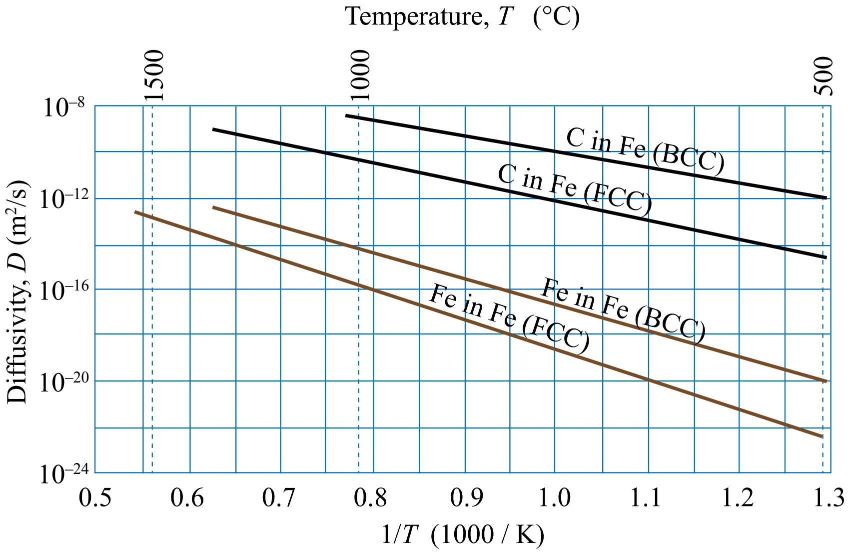
Styrene (graft)

Problem	Possible	Score
1	20	
2	20	
3	20	
4	20	
5	20	
TOTAL	100	

1. Diffusion

The plot reproduced here is from L.H. Van Vlack, *Elements of Materials Science & Engineering*, 4th edition, Addison-Wesley Publishing Co., Inc. Reading, MA (1980).

Explain the format of this data presentation, comparing and contrasting the four data sets shown here, using sketches to illustrate your rationale.

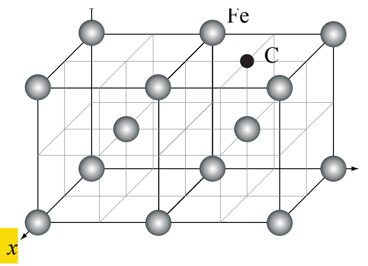


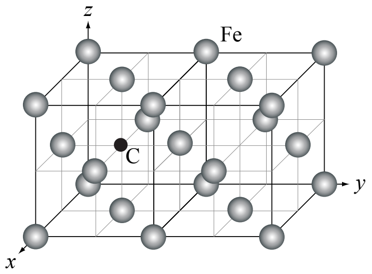
ANSWER: The format of this data presentation, ln D vs $1/T$, is the standard for phenomena exhibiting **Arrhenius-type behavior**. Diffusion is one such phenomenon, as evidenced by taking the natural log of both sides of the equation for diffusivity given in the Worksheet, as follows

$$\ln D \;=\; \ln D_0 - \left(\frac{Q}{\mathrm{R}}\right)\left(\frac{1}{T}\right)$$

revealing the equation for a straight line on a plot of ln D vs $1/T$. The most important parameter revealed by a plot in this format is the slope of the line, giving the **activation energy *Q*** for diffusion.

Comparing and contrasting the four data sets show they all have different diffusivities and different activation energies. The diffusion of carbon in iron (either BCC or FCC) occurs more readily than the "self" diffusion of iron in iron (either BCC or FCC), indicated by their higher diffusion coefficients (D) and the smaller slopes of their respective lines, associated with lower activation energies. The reason for this is a **difference in diffusion mechanisms**. Carbon diffuses **interstitially**, while iron diffuses substitutionally, by a **vacancy mechanism**. Interstitial diffusion is more rapid, and has a lower activation energy than substitutional diffusion. Moreover, in both cases there are differences in diffusivity and in slope indicating that diffusion of any type (interstitial or substitutional) in the BCC structure occurs more readily than in the FCC structure. Once again this is associated with the activation energy for diffusion being lower for the more open BCC structure than the more densely-packed FCC structure. Sketches reveal this quite clearly, showing C in octahedral interstitial locations in both structures, and the lower density of the BCC structure compared to the FCC structure.





2. Phase Diagrams

Complete the binary phase diagram below using the following data.

Nickel is an FCC metal that melts at 1455°C; niobium is a BCC metal that melts at 2471°C.

Ni_3Nb β phase has orthorhombic symmetry. At 1402°C, β phase of 34.5% Nb melts congruently.

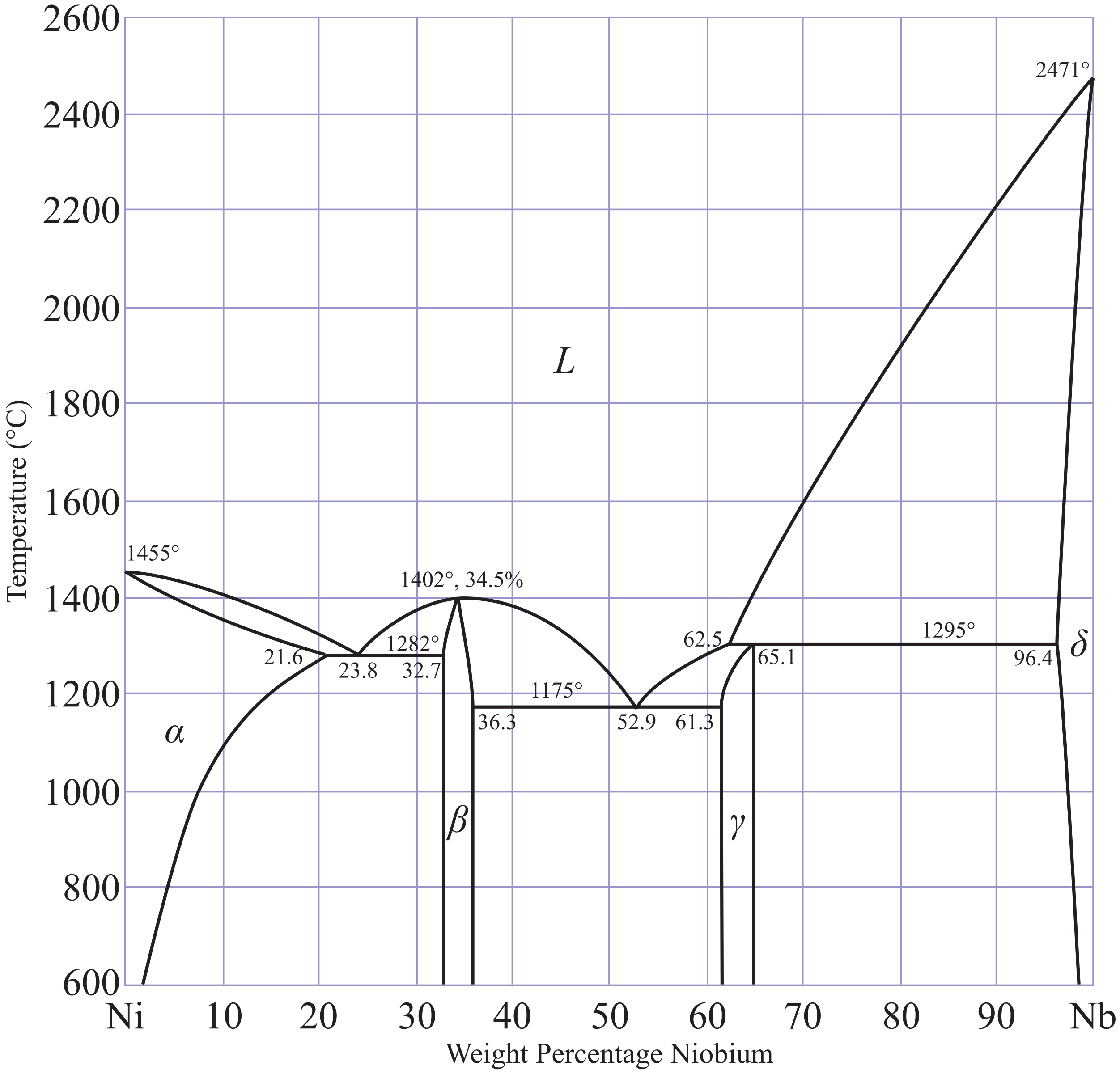
NiNb γ phase has rhombohedral symmetry. At 1295°C, γ phase of 65.1% Nb melts to form liquid of 62.5% Nb and δ phase of 96.4% Nb.

At 1282°C: liquid of 23.8% Nb solidifies to from α phase of 21.6% Nb and β phase of 32.7% Nb.

At 1175°C: liquid of 52.9% Nb solidifies to form β phase of 36.3% Nb and γ phase of 61.3% Nb.

At 600°C: an alloy of 10% Ni consists of two phases, γ of 65.1% Nb and δ of 98% Nb; an alloy of 50% Ni consists of two phases, β of 36.3% Nb and γ of 61.3% Nb; and an alloy of 90% Ni consists of two phases, α of 3% Nb and β of 32.7% Nb.

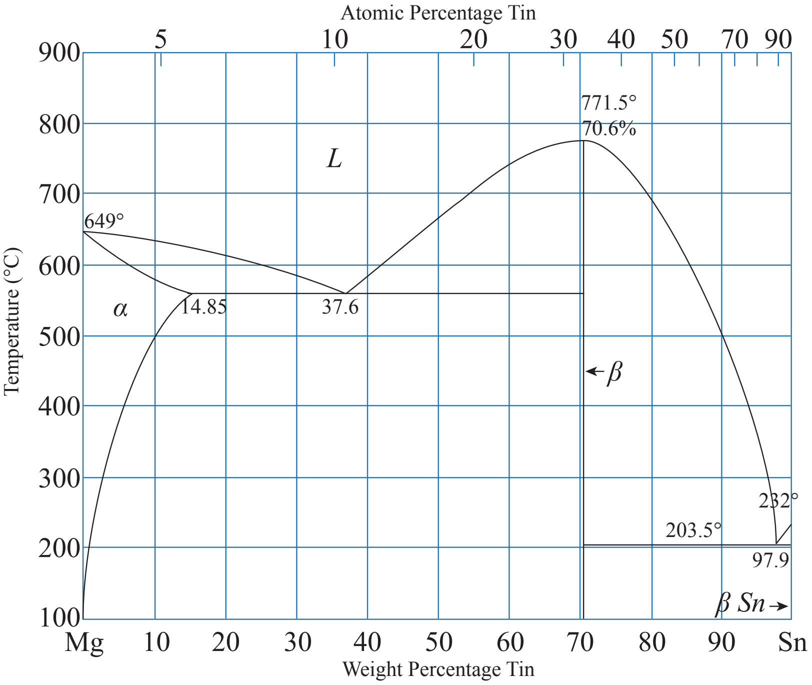
ANSWER:



3. Kinetics

A lightweight carrier bearing housing on a BART train is damaged in a collision, quickly "straightened" in the company machine shop, then given to you for follow-up heat treatment with an incentive bonus ($) to "get the train running again" within 3 hours. The Mg alloy component is known to contain 10-12 wt% Sn, and is conventionally strengthened by precipitation of FCC Mg_2Sn particles.

Specify a thermal treatment to restore load-bearing properties in this component. Explain the microstructural evolution at each step, accommodation of the "straightening" treatment, and your protocol for pursuing the incentive bonus.



ANSWER: To "restore" the load-bearing properties of this component, it must first be appreciated that the carrier bearing housing was "straightened" by plastic deformation, increasing its dislocation density enough to require the "follow-up heat treatment" requested of you. Such a treatment, also known as **annealing**, restores ductility by removing damage caused by cold work. Annealing requires elevating the temperature to enable diffusion, generally 1/3 to 1/2 of the "melting" temperature or first appearance of a liquid phase, and holding for sufficient time to complete one or more of the three stages of annealing, recovery, recrystallization, and grain growth. The concern in this case is overdoing it. Annealing to the point of excessive grain growth can be detrimental to a load-bearing component because it can result in significant softening.

However there is more complexity to this case because of the information given in the problem statement that this alloy conventionally derives its strength from precipitation hardening (not "work-hardening").

An annealing treatment in the required temperature range for a 10-12% alloy (≈190 –– 280° C) would cause the initial precipitate distribution (present at the outset for strengthening) in the deformed alloy to **coarsen**, which results in softening. Consequently the appropriate thermal treatment in this case would be one that **re-establishes the fine precipitate distribution associated with age-hardening**.

Protocol: Begin with a homogenization treatment at 530 – 540°C for sufficient time to generate a solid solution of *α* phase and simultaneously allow recovery and recrystallization to run to completion. Rapidly quench to establish a supersaturated solid solution of *α* phase. Age for sufficient time at the lower end of the diffusion-enabled temperature range (≈200°C) to generate a fine dispersion of *β* phase (Mg_2Sn) precipitates. To establish and confirm treatment times, verify all treatments by a few non-destructive hardness tests and/or x-ray diffraction runs at each step, especially before releasing for final installation.

Incentive (?): It would be unethical to pursue the incentive bonus in this case because of the safety concerns associated with a passenger train.

4. Failure of Engineering Materials

The January 2011 publication of Consumer Reports™ addresses safety issues raised by consumers in an article entitled "Glass Bakeware that Shatters —We put Pyrex and Anchor Hocking Dishes to the Test."

Explain, citing your knowledge of thermal shock, how these three bullet points serve as "safety rules" to "minimize" glass shattering, critiquing their effectiveness from a materials engineering perspective.

Expert • Independent • Nonprofit

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This article appeared in
January 2011 Consumer Reports Magazine.

To minimize the chances of glass bakeware shattering, read and save the safety instructior
are some safety rules to follow:

- Always place hot glassware on a dry, cloth potholder or towel.
- Never put glassware directly on a burner or under a broiler.
- Always allow the oven to fully preheat before placing the glassware in the oven.

ANSWER: Thermal shock is a consequence of two intrinsic properties: thermal expansion and thermal conductivity. It is called thermal "shock" when **differential thermal expansion** between surface and interior leads to catastrophic failure of a component placed in a steep temperature gradient. The reason thermal expansion is "differential" for materials such as ceramics and glasses is **poor thermal conductivity**, which prohibits heat flow that would flatten the temperature gradient, allowing surface and interior to either expand or contract at the same rate.

Addressing the safety rules in order,

1) Placing hot glassware on a dry cloth potholder or towel **retains heat** at the surface, **reducing the temperature gradient from surface to interior**, slowing thermal contraction at the surface, thereby reducing differential thermal contraction at the surface relative to the interior. The surface is therefore less likely to be placed in residual tension, inhibiting catastrophic crack growth. This is an EFFECTIVE practice.

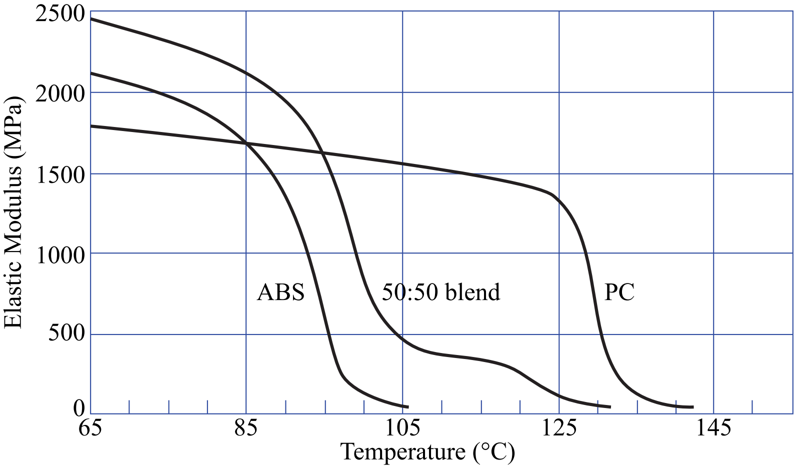
2) Never putting glassware directly on a burner or under a broiler **separates** the glassware from the high heat source, **reducing the temperature gradient from surface to interior**, slowing thermal expansion at the surface, thereby reducing differential thermal expansion at the surface relative to the interior. The interior is therefore less likely to be placed in residual tension, inhibiting catastrophic crack growth. This is an EFFECTIVE practice.

3) Allowing the oven to fully preheat before placing the glassware in the oven **immerses** the glassware in a high temperature environment rather than allowing it to slowly heat as the oven temperature increases, **increasing the temperature gradient from surface to interior**, accelerating thermal expansion at the surface, thereby increasing differential thermal expansion at the surface relative to the interior. The interior is therefore more likely to be placed in residual tension, aggravating catastrophic crack growth. This is an INEFFECTIVE practice. It is possible that this advisory seeks to avoid the "overshoot" of poor oven thermostats causing much higher temperatures than the preset values, or poor oven design, wherein the heating coils are too close to the cookware to employ practice (2) above. In any case, SLOW HEATING / COOLING is **always preferable** to rapid heating/cooling because of the **poor** thermal conductivity of glass.

5. Polymers

In their 2008 paper "Experimental Investigation of the Viscoelastic Deformation of PC, ABS and PC/ABS alloys," published in *Materials Letters* vol. **62**, pp. 2750–2753, authors Z.N.Yin *et al* examine the behaviors of two well-known thermoplastics, polycarbonate (PC), and acrylonitrile-butadiene-styrene (ABS), before and after "alloying." Data collection was halted as soon as "viscous" flow was detected, and a summary plot of their data for three compositions is shown here.

Compare and contrast these behaviors in detail, citing your knowledge of viscoelasticity in polymers.



ANSWER: The data presented here isolates the elastic portion of the viscoelastic performance curve by halting testing as viscous flow begins. Consequently only elastic behaviors can be compared and contrasted.

Considering first the individual constituents, revealed in the problem statement to both being thermoplastics with linear chain-like configurations shown on the worksheet page, both are expected to deform elastically by the **uncoiling and sliding** of their covalently-bonded backbone chains. It is seen that ABS has higher elastic modulus at lower temperature than PC, explained by the acrylonitrile and styrene **grafts** extending off the butadiene backbone, colliding with one another and obstructing the relative motion of ABS chains past one another during elastic deformation. Polycarbonate has much **less steric hindrance** because it has no such extensions protruding from the backbone chain, explaining its lower elastic modulus at lower temperature. One of the most salient structural differences between these polymers is the location of their phenol groups: for ABS, the phenol is in one of the grafts, making that graft even more cumbersome during its deformation-induced motion, while for PC, two phenols are integral to the backbone.

The effect of increasing temperature on ABS is more pronounced for the same reason: diffusional motion enables the grafts, however cumbersome they might be, to more easily evade one another during uncoiling and sliding, generating a lower **glass transition temperature** (vertical drop in modulus) in ABS than in PC.

The most interesting result here is the behavior of the 50:50 polymer blend, which has a **higher** elastic modulus at low temperatures than either of its constituents, PC or ABS. The reason for the higher rigidity of the blend is the **increased resistance to chain uncoiling and sliding** caused by the **interpenetration of the chains** from the PC and ABS constituents. This is an example of property enhancement by control of polymer microstructure through "blending," which the authors of the paper term "alloying," a term that is more common and appropriate in the materials engineering context.