1. True or False (reason your answer if you think the statement is false) (12%):

(a) Graphite is soft because of the weak sp^2 C-C bond strength. (2%)

(b) It is possible to manufacture a single crystal without dislocations or vacancies at room temperature. (2%)

(c) Let ϕ represents the angle between the normal to the slip plane of a BCC crystal and the applied stress direction, and λ represents the angle between the slip and stress directions. Typically, $\phi + \lambda > 90°$. (2%)

(d) Because the α + L two-phase coexisting state in the Cu-Ni binary system under given pressure at 1 atm appears as a "field" in the binary phase diagram, the "number of degrees of freedom" is 2. (2%)

(e) Using $\sigma_T = \sigma(1+\varepsilon)$ and $\varepsilon_T = \ln(1+\varepsilon)$ equations, the true stress (σ_T) and strain (ε_T) may be transferred from engineering stress (σ) and strain (ε). Those equations are invalid beyond the necking point, though. (2%)

(f) Because engineering fatigue data are impractical to collect from normal laboratory tests, we need to employ the Larson–Miller parameter to conduct data extrapolation. (2%)

2. The concentration of substitutional solute atoms in solids (11%):

(a) A researcher, Guang-En, wants to calculate the density of a hypothetical A-4.4wt.%B alloy. The information Guang-En has obtained is listed as follows:

1. A and B atomic masses are 26.981 amu and 63.456 amu, respectively.
2. B atoms present in the form of random substitutional solute in A matrix forming an FCC lattice.
3. The lattice parameter of this FCC crystal is a function of B atomic percentage and temperature: $a(X,T) = 4.0393 - (5.3092 \times 10^{-3})X + (1.2737 \times 10^{-4})T$. Here X is the atomic percentage in unit "at.%B," and T is the temperature in unit "°C."

Based on the information provided, calculate the mass density of A-4.4wt.%B at 540°C. (4%)

(b) Now, Guang-En wants to diffuse Z atoms into an X wafer using predeposition and drive-in heat treatments. The X wafer initially has a background concentration of Z atoms $C_Z = 2 \times 10^{20}$ atmos/m^3. In the first, or predeposition step, impurity Z atoms are diffused into the X wafer, and the surface composition of the Z, C_{surf}, also remains constant over time 3×10^{26} atmos/m^3. The suggested predeposition treatment time, t_{pre}, is 10 minutes. We may approximate the total surface concentration of Z impurities in the X solid that was introduced during the predeposition treatment, Q_{pre}, as:

$$Q_{pre} \approx 2C_{surf}\sqrt{\frac{D_{pre}t_{pre}}{\pi}}$$

where D_{pre} represents the diffusion coefficient of Z atoms in X solid during predeposition, and the unit of Q_{pre} should be atoms/m^2. The second "drive-in diffusion" treatment is used to transport Z atoms farther into the X wafer in order to provide a more suitable concentration distribution without increasing the overall impurity content. This treatment is carried out at a higher temperature, 1200°C, in an oxidizing atmosphere to form an oxide layer on the surface. The diffusion of Z atoms through this XO_2 layer is slow, so very few Z atoms diffuse out of and escape from the X wafer. After "drive-in diffusion," the junction depth, x_{jct}, representing the x-position where the diffusing Z concentration is just equal to C_Z, can be approximated as:

$$x_{jct} \approx \left[(4D_{drv}t_{drv})\ln\left(\frac{Q_{pre}}{C_Z\sqrt{\pi D_{drv}t_{drv}}}\right)\right]^{1/2}$$

where D_{drv} and t_{drv} are "the diffusion coefficient of Z atoms in X solid" and "time period," respectively, during "drive-in diffusion" treatment. If Guang-En wants to achieve $x_{jct} = 2.5$ μm after two hours of "drive-in diffusion" treatment, what predeposition temperature

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should he use? For the diffusion of Z in X, the preexponential factor and diffusion activation energy are 7×10^{-5} m^2/s and 3.65 eV/atom, respectively. (7%)

3. **Crystallization kinetics of a fluxing agent (6%):**

A fluxing agent initially in its liquid form crystallizes at a temperature T below the melting point of this fluxing agent; the fraction of crystallization, X, as a function of the crystallization time, t, and the isothermal holding temperature, T, may be represented as the "extended" Avrami equation shown in the following:

$$X(T,t) = 1 - \exp\left\{-\left[k_0 \exp\left(-\frac{E_a}{RT}\right)(t-\tau)\right]^n\right\}$$

where k_0 is the preexponential factor, E_a is the activation energy of crystallization, R is the gas constant, τ is the incubation time, and n is the Avrami exponent associated with the nucleation and growth mechanism. Explain how we can vary T, t, and conduct linear regression to obtain constants k_0, E_a, τ, and n. (6%)

4. **The research and development in titanium alloys (11%):**

(a) A pure titanium originally at 1066°C would transform from BCC βTi to HCP αTi at 883°C. However, if adding β-stabilizing elements such as vanadium, an appreciable amount of βTi phases can be retained at room temperature. Nowadays, Ti-6Al-4V (wt.%) has been the most widely used titanium alloy where αTi and βTi coexist. One of the typical heat treatments is the slow furnace cooling the solution-treated Ti-6Al-4V from 1066°C (~50°C above βTi→αTi transformation temperature). While conducting X-ray diffraction (XRD) analysis with a wavelength of 1.54Å on the cooled specimen, there are peaks at 2θ=35°, 39°, 40°, 41°, 54°, 58°, 64°, 72°, and 75° in the XRD pattern. By understanding (i) 2θ=35° corresponds to $\{10\bar{1}0\}$ plane of HCP αTi with c/a ratio 1.582, and (ii) 2θ=40° corresponds to $\{110\}$ plane of BCC βTi, index the remaining peaks. (5%)

Note 1: the interplanar spacing formula for hexagonal crystals is:

$$\frac{1}{d^2} = \frac{4}{3}\left(\frac{h^2+hk+k^2}{a^2}\right) + \frac{l^2}{c^2}$$

Note 2: the rule of missing reflection for HCP crystal is:

$$h + 2k = 3N \text{ and } l \text{ is odd } (N \text{ is an integer})$$

(b) Determine the critical crack length for a through crack within a thick plate of a Ti-6Al-4V alloy with an equiaxed grain structure that is under uniaxial tension. The fracture toughness K_{Ic} is 66 MPa$\sqrt{m}$ and its fracture stress is 910MPa. Assume $Y = 1$ in the fracture toughness equation. (3%)

(c) Another typical heat treatment for Ti-6Al-4V alloy is water quenching from 1066°C. This heat treatment is expected to let Ti-6Al-4V form a structure consisting of all "titanium martensite," plate-like HCP, and its lattice parameters are slightly different from HCP αTi. However, "titanium martensite" is relatively soft compared to iron-carbon martensite in steel. Explain why "titanium martensite" is softer by first listing three important strengthening mechanisms of "iron-carbon martensite" and then indicating one of those mechanisms is nearly absent in "titanium martensite." (3%)

5. **The polished section of one sintered CeO_2 specimen is shown below. The specimen was sintered at 1500°C for 1 h. The grain boundaries were revealed by thermal etching at 1400°C for 0.5 h. (10%)**

(i) What is roughly the relative density of the specimen ?

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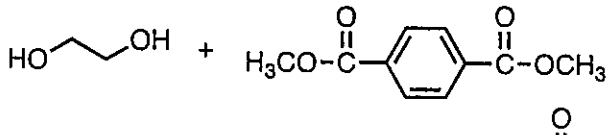
(ii) What is roughly the size of the CeO_2 grains ?

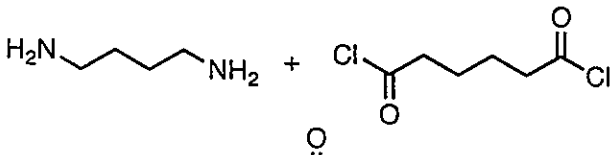
6. The iron ions in Wustite (iron oxide) can exist in both Fe^{2+} and Fe^{3+} states. In order to maintain the electroneutrality, the chemical formula for Wustite is often represented as Fe_xO. (10%)

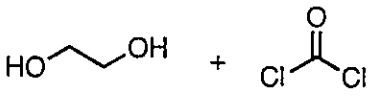
(i) Please choose from (a) x<1.0 or (b) x=1.0 or (c) x>1.0, which one is correct.

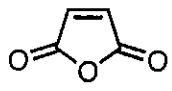
(ii) Please explain briefly.

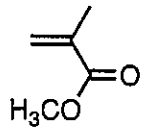
7. Draw the repeat units of the polymers formed from the following monomers: (2 pts x 5 = 10 pts):

(a) 

(b) 

(c) 

(d) 

(e) 

8. Sketch the chemical structure of SBS copolymer (5 pts). Why is it a thermoplastic elastomer? (5 pts)

9. What are low dielectric constant (low-K) materials and high dielectric constant (high-K) materials used in silicon-based semiconductor techniques? Why low-K and high-K materials are essential for advanced CMOS technologies? (10%)

10. Please describe the relationships among permittivity, electric dipole momentum, polarization vector, electric susceptibility, and complex refractive index. What is the dispersion behavior of permittivity with frequency? (10%)

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