

Solutions Exam Materials Science Jan. 27 2015

- 1a. Slightly higher than 600 C (600 C is also correct). The alpha phase that then forms contains ~4 wt.% Mg.
- b. Around 520 C (510 and particularly 530 are bad estimations). The last liquid then contains ~24 wt.% Mg.
- c. At 400 °C single phase, 100% alpha (1 pt). At 200 °C: $(36-10)/(36-4) = 13/16$ alpha and thus 3/16 beta (2 pt).
- d. This alloy contains precipitates of beta in a matrix of alpha (can be preference for beta at grain boundaries of alpha, but also inside alpha grains). Beta occupies about 7/33 is slightly more than one fifth of the weight. (Since the beta precipitates out of the solid alpha they will be relatively small.)
- e. Solid solution hardening by annealing to about 450 C and then rapid cooling. Precipitation hardening: First solid-solution hardening and the shortly followed by annealing order of a few hours at 150-200 C to form optimized number density and size and structure of precipitates to achieve peak hardness. In both cases the aluminum becomes stronger because the solute Mg atoms or the precipitates hinder dislocation mobility and this directly leads to increased strength and hardness (Precipitation hardening is more effective. Cold work and grain refinement are also possible but have not any direct relation to the phase diagram.
- f. Al: $\{111\}\langle 1-10\rangle$, 4x3 is 12 slip systems, Mg: $(001)\langle 110\rangle$, 1x3 slip systems. A correct plane is half point, a correct direction is half point and correct number of slip system is 1 point, gives a maximum of 4 points.

2a. Useful reasons are: 1. Improved wear resistance (hardness or scratch resistance of surface), 2. Improved corrosion resistance, 3. Improved high temperature resistance of surface (but this is not clear advantage), 4. For decorative purposes (black surface).

b. Stress in steel is:

$$\sigma_{//} = \frac{E\varepsilon}{1-\nu} = \frac{212 \cdot 10^9 (0.2/200)}{1-0.29} = 299 \cdot 10^6 \text{ Pa} = 299 \text{ MPa}$$

Stress in TiC is:

$$\sigma_{//} = \frac{E}{1-\nu} (\Delta\alpha \Delta T + \varepsilon) = \frac{449 \cdot 10^9 (-7 \cdot 10^{-6} \times 680) + 0.2/200}{1-0.19} = 2.08 \text{ GPa}$$

- c. Yes, the stresses due to cooling are favourable, because the shrinkage upon cooling is more severe for the steel than for the TiC coating and this puts the coating under (in-plane) compressive stress. The coating is a ceramic material. Ceramic materials can be loaded well in compression, but behave very poorly during tension because of their brittleness and low fracture toughness. For similar reasons pre-stressed concrete creates by steel bars compressive stresses in the concrete and then it can be used in more heavily loaded horizontal plates in bridges etc., which otherwise would not be allowed.
- d. When steel is loaded beyond the yield stress it will start to deform plastically, which means that atomic crystal planes by the movement of dislocations will effectively slide irreversibly with respect to each other. In the crystals the dislocations can move relatively easy, but grain boundaries are obstacles for dislocation movement and thus reduce plastic deformation. The smaller the grains the more obstacles and the harder the material (more resistive to plastic deformation).
- e. Highest yield strength occurs for cold-rolled 0.45 wt% C steel. In cold rolled steel dislocation density is much higher than in recrystallized steel. The dislocations mutually hinder each other movement and therefore with higher density increases strength/hardness. More carbon can create more solid-solution hardening and thus higher strength. However in steel more carbon leads to more pearlite (Fe₃C lamellae) which is the much harder (and more brittle) phase and thus increases strength/hardness.
- f. 1 pt: Ceramics are characterized by ionic or covalent bonds (or a mixture), whereas in metals of course metallic bonds occur. These differences in bonds intrinsically make metals (much) better plastically

deformable than ceramics. 1 pt: Since ceramics are not plastically deformable they cannot increase the crack tip radius at relatively sharp cracks and therefore cannot reduce very high local stresses due to stress concentrations at the crack tip. Metals can increase tip radius and can reduce the high local stresses. 1 pt: Fracture toughness is a measure for the amount of load (towards a certain nominal stress) a material can still bear when a sharp crack is present and because of arguments of previous point is thus generally low for ceramics and high for metals.

3a. 1. Diamond with 4-fold coordination (sp^3 -hybridization), 2. Graphite with 3-fold coordination in planes (sp^2 -hybridization) and vdWaals bonding between planes, Graphene is one such plane of graphite 3. Fullerenes, e.g. C60 buckyballs, 4. Carbon nanotubes (single wall or multiple walled) 5. Amorphous carbon.

b. The maximum for 2-fold coordination is the minimum for the 3-fold coordination. This is an equally sided triangle where on the corners the anions are position and in the center of gravity the cation. From geometry (Pythagoras) it can be derived that $\frac{2}{3}$ times square root of 3 times anion radius is equal to one anion plus one cation radius. r_C/r_A is thus $\frac{2}{3}$ times square root of 3 minus one.

c. $0.4 \times 30000 + 0.3 \times 40000 + 0.2 \times 50000 + 0.1 \times 60000 = 12000 + 12000 + 10000 + 6000 = 40000$ g/mole.

d. $0.3 \times 30000 + 0.3 \times 40000 + 0.25 \times 50000 + 0.15 \times 60000 = 9000 + 12000 + 12500 + 9000 = 42500$ g/mole.

e. Polyisoprene is at room temperature a rubber (above T_g) and PVC a glass (because below T_g) and therefore PVC has a higher stiffness. For the estimate of the difference it is important that the student mentions that it is several orders of magnitude, i.e. at least a factor 100. They do not have to give absolute values like the rubber is of the order of MPa and the glass is several GPa, but this is of course excellent. The maximum strain of PVC is in-between 0 and 100% and for PI several hundred % like 500%.

4a. Essential in the electron band structure of semiconductors is presence of a band gap, i.e. sufficient energy (like thermal) is required to promote electrons from the valence band across the bandgap to the conduction band and to produce free (conduction) electrons. The probability that this occurs increases exponentially with temperature and this dominates the temperature dependence of the electrical conductivity which thus approximately also increases exponentially with temperature. Metals do not have a bandgap and therefore free (conduction) electrons are always abundantly available and do not influence the temperature dependence of the electrical conductivity. In contrast, this temperature dependence is determined by the electron mobility and the mobility decreases with increasing temperature, because at higher temperature atoms vibrate more heavily by which free electrons experience more scattering (by phonons). Therefore the resistance increases (more or less linearly) with temperature. In semiconductors the mobility also decreases with increasing temperature, but this is a small effect compared to the increase in number of free electrons.

b. The conductivity increases, because similar like in 5a. energy is required to promote electrons from the valence band across the bandgap to the conduction band and to produce free (conduction) electrons. This energy can, apart from temperature, also be provided by visible light.

c. 475 C is about 750 K. Room temperature is about 300 K. So, the temperature is increased about a factor 2.5. Since, the resistivity is approx. directly proportional to temperature, the resistivity increases also by a factor 2.5. The conductivity thus decreases by a factor 2.5 and thus becomes $\sim 1 \times 10^6 (\Omega m)^{-1}$.

d. Sample 1 is an intrinsic semiconductor and sample 2 an n-type extrinsic semiconductor, because a phosphor atom contains 2 extra electrons compared to an indium atom. Thus when In atoms are replaced by P atoms we donate (free) electrons to the system and definitely not holes.

$$e. \sigma = n|e|\mu_e = \frac{2}{10^7 (0.586 \cdot 10^{-9})^3} \cdot 0.16 \cdot 10^{-18} \cdot 0.50 = 79.5 (\Omega m)^{-1}$$

5a. In a refrigerator a steady-state condition can be created because of a constant maintained temperature difference between inside and outside. In this case for thermal isolation thermal conductivity has to be minimized and therefore certain types of polymer *foams* are the best choice.

b. In a cooler box a steady-state condition is not maintained and heat will continuously diffuse in and eventually the inside temperature will become equal to the outside temperature. In this case for thermal isolation thermal diffusivity has to be minimized and therefore certain types of **elastomers** are (only based on this argument) the best choice.

c. Bonus.

d. The I profile provides more resistance to bending than the H-profile, because in the formula for the second moment of area and thereby in the shape factor, infinitesimal pieces of area contribute to the integral after multiplication by the distance to the bending axis squared. In the I profile it is clear that much more cross-sectional area is at larger distance from the bending axis than for the H profile and this integral will yield a much larger I_{xx} and shape factor.

e. Shape factors have an important influence, because the attainable shape factor is depending on the type of material and therefore influences the type of material that is the best choice for a certain application. To give an example, for low weight constructions applied under torsion or bending, massive steel products can never compete with wood product. However, steel can be produced with very high shape factors (e.g. 50), e.g. thin walled tubes, which is impossible for wood, which cannot have shape factors much above 1. Therefore, without shape factor wood will be the best choice, but with shape factor steel can become the best choice.