Solutions Exam Materials Science Nov.6 2015

1a. About 1470 C, clearly above 1450 and below 1493 C. The composition is about 0.4 wt.% C (0.3 and 0.5 can be accepted, but not outside this range).

b. About 1360 C (plus min max 10 C). About 2.05-2.1 wt.% C.

c. 0.95=(6.7- x)/(6.7-0.76) or 0.05=(x-0.76)/(6.7-0.76), which both lead to x=1.057 wt.%C.

d. 1200 C: 100% gamma (1 pt). 726 C: fr. alfa = (6.7-1.0)/(6.7-0.022)=0.854 (1 pt), fr. Fe3C = (1.0-0.022)/(6.7-0.022)=0.146 (1 pt).

e. At 727 C (1 pt). Pearlite: fr. alfa = (6.7-0.76)/(6.7-0.022)=0.889 (1 pt), fr. Fe3C = (0.76-0.022)/(6.7-0.022)=0.111 (1 pt).

f. Cold rolling increases strength, because increases dislocation density and since dislocations are mutual obstacles during their movement, decreases dislocation mobility and thereby increases (yield) strength (1 pt). Cold rolling creates texture and this leads to anisotropic properties (i.e. properties are not the same in different directions. This is often not acceptable (1 pt). Annealing leads to recrystallization and thereby removes texture and anisotropy (1 pt). Cycles of cold rolling and recrystallization generally are used to refine the grains of the material. Smaller grain size leads to relative more grain boundary area (per unit volume) and since boundaries are obstacles for dislocations movement, decreases dislocation mobility and thereby increases (yield) strength (1 pt).

2a)

$$\sigma = \frac{F}{A} = \frac{100000 \, kg}{25 \, cm^2} = 4000 \, kg/cm^2 \approx 400 \, MPa$$

b)

$$\varepsilon_{//} = \frac{\Delta l}{l} = \frac{0.01}{5} = 0.002 = 0.2\%$$

c)

$$\sigma = E * \varepsilon_{//} \rightarrow E = \frac{\sigma}{\varepsilon_{//}} = \frac{400 \, MPa}{0.002} = 200 \, GPa$$

d) $((1+\varepsilon_\downarrow)^2 - 1) * 100\% = (2\varepsilon_\downarrow + \varepsilon_\downarrow^2) * 100\% \approx 2\varepsilon_\downarrow * 100\% = 2 * -v * \varepsilon_{//} * 100\% = 2 * -0.3 * 0.002 * 100\% = -0.12 \%$ (the minus thus means reduction in area).

e) On a macroscopic scale the **length of the arm will increase permanently** after the loading beyond 40000 kg, because of plastic deformation (1 pt). Up to 40000kg the loading is fully elastic. On an atomic scale plastic deformation normally means that **atomic planes start sliding with respect to each other** (1 pt). This sliding occurs by the movement of dislocations. (An alternative mechanism for plastic deformation is twinning, but this is not treated during this course.)

f) Yes, it makes a large difference, because in crystalline systems plastic deformation can occur by sliding of crystal planes with respect to each other. In amorphous materials slip along planes is impossible (there are no planes) and therefore such materials are very resistant to plastic deformation (are very hard), but also very brittle (very low fracture toughness) and cannot be used with any reliability under tensile loading. Construction elements subjected to tensile loading will never be made of an amorphous material.

3a. Hardness, wear resistance, corrosion resistance, higher operation temperatures, lower density.

b. Fracture toughness for ceramics is much lower than of metals, because of difference in bonding. Covalent/ionic for ceramics versus metal bonding for metals (1 pt). Delocalized electrons in metal bonding act as a bonding 'sea' which makes it relatively easy for atomic planes to slide with respect to each other by movement of dislocations. Localized electrons in case of covalent/ionic bonding makes it much harder for dislocations to form and also when dislocations are present generally reduce dislocation mobility (1 pt). Sufficient high dislocation mobility is crucial to ensure sufficient high fracture toughness, because by dislocation movement sharp crack tips become blunted and by increasing tip radius stress concentrations reduce and the material is resistant to crack propagation and this resistance is a direct measure of fracture toughness (1 pt).

c. Cis and trans can only occur when a double bonded C atom pair (C=C) is present per repeating unit in the main chain of the polymer molecules (1 pt). In case of cis the continuation of the chain occurs on the same side of C=C and in case of trans occurs at the opposite side (1 pt).

d. Below Tg the polymer is a glass and beyond Tg it becomes rubbery; the stiffness decreases several orders of magnitude with increasing temperature around Tg (1 pt). With very slow loading the polymer behaves mechanically like a viscous liquid, so with very low stiffness, low yield strength and plastic deformation by viscous flow (1 pt). With very fast loading the polymer behaves mechanically like a glass, so with high stiffness, high strength, nearly only elastic loading, thus fracture are very limited plastic deformation by viscous flow (1 pt).

e. Weight average molecular weight: 0.2x200 + 0.3x400 + 0.3x600 + 0.2x800 = 40 + 120 + 180 + 160 = 500 (1 pt).

Number average molecular weight: The number fractions can be obtained from the weight fractions by dividing by the relative weights of the 4 types of molecules and then normalizing these fractions to a total of 1. Therefore it holds (0.2 + 0.3/2 + 0.3/3 + 0.2/4)C=1, which thus provides C=2. Therefore the number fractions are 0.4, 0.3, 0.2 and 0.1, resp.. Number average molecular weight: 0.4x200 + 0.3x400 + 0.2x600 + 0.1x800 = 80 + 120 + 120 + 80 = 400 (2 pt).

4a. Buckling will occur by bending towards the y-direction (1 pt), because in this direction the material is closer to the central x-axis. In the x-direction material is more distant from the central y-axis. The more distant the material the more it will resist bending. In the y-direction there is the least resistance to bending (1 pt).

b. According to the graph the best materials are wood parallel to the grain, particular on the light density side, thus Balsa. Another one similar good is CFRP (carbon fiber reinforced polymer) Uni-ply. (1 pt). However, to make both types of materials with an I shape is not efficient. For wood a lot of material has to be wasted and to make CFRP in this shape will be relatively expensive. Only in real high performance applications where price is not a direct issue CFRP will be chosen (1 pt). A 3rd option could be engineering ceramics with highest $E^{(0.5)}/\rho$ ratio. However, buckling will create tensile stresses in the material and then engineering ceramics are not a proper option. The same holds for glasses, porous ceramics, etc. (1 pt) Then the most logical next option is engineering alloys, because they can be cheaply produced (e.g. extruding) in an I shape. The most logical choice with the highest $E^{(0.5)}/\rho$ ratio from the engineering alloys is then Al Alloys (1 pt). Also from price point of view this material will be reasonable acceptable. Of course Steels will be clearly cheaper, but then the solution has lost its relation with optimizing the $E^{(0.5)}/\rho$ ratio.

c. In tension the best materials have the highest values for E/ρ. Now CFRP Uni-ply stand out as the single best material (1 pt). However, same arguments holds as in b. (to make CFRP with an I shape is

not efficient and CFRP itself is already expensive.). Now the most logical choice appears Steel, because has the same(similar) performance as e.g. Wood Parallel to Grain, Al Alloys, Ti Alloys, but is much cheaper. (1 pt)

d. An I shaped column is efficient when the bending occurs controlled towards the x-direction (e.g. when it is a beam under a floor or roof), but not in this compressive case where bending will occur towards the y-direction. To improve the shape a hollow thin-walled square shape is clearly better. However, when the bending direction is not controlled a hollow thin-walled circular cross-section is better than a square one.

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a. High heat conductivity kappa prevents the TE material from effectively using the available heat gradient. High value for kappa in the denominator makes Z small. (1 pt) Also (but not expected from students): electrons can move freely across the metal due to the absence of a band gap, so the Seebeck coefficient of metals is typically low compared to semiconductors (e.g. Si =400*Pt).

b. Very low value for the electrical conductivity sigma makes Z small. (1 pt) Correct argument not expected from students: Typically kappa also reduces when sigma reduces, but, since kappa not only is heat conduction by free charge carriers but also by lattice vibrations (phonons), kappa is not going to zero when sigma is going to zero and therefore Z has to reduce to very low values when we decrease conductivity towards insulating behaviour.

c. Like mentioned under b heat conduction occurs by (1) free charge carriers, e.g. conduction electrons and (2) lattice vibrations (phonons).

d. Clear sketch showing Freeze out, exhaustion or extrinsic regime, intrinsic regime (with those written in. various slopes are nice but not compulsory); see figure to the right.

e. n-type, because, as directly observable in the periodic table, I contains additional valence electrons (in the outer shell) compared to Pb and Te. (1 pt) (One additional valence electron compared to Te and 3 more than Pb.) Thus, I doped in PbTe will create electron donor level easily creating

free (conduction) electrons and not holes. Performance Z is increased because doping increases electr. conductivity σ, and does not with the same ratio increase thermal conductivity κ (2 pt). In fact, doping might hinder phonons, lowering their contribution to κ (although for realistic doping levels this effect is minimal). However, κ will also increase due to heat conduction by the
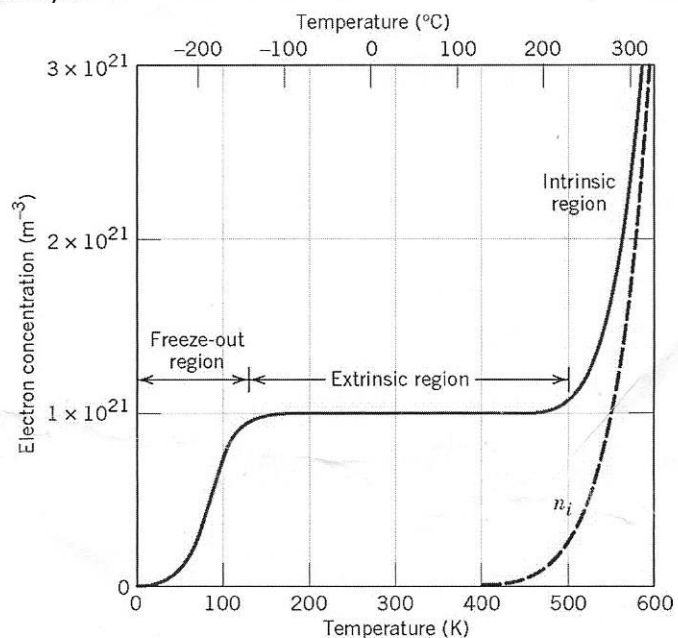
increased number of charge carriers. However, since the phonon contribution to κ is significant, doping will increase σ more than κ and therefore Z increases.

f. $\sigma = n|e|\mu_e + p|e|\mu_h$, p>>n, n is negligible (can be taken zero) and therefore:

$$p = \frac{\sigma}{|e|\mu_h} = \frac{3.6}{1.6\,10^{-19}\,0.045} = 5.0\,10^{20}\ \text{m}^{-3} = 500\,\mu\text{m}^{-3}$$