Exam Materials Science

January 26, 2021, 15:00-18:00

- *Clearly indicate your name and student number on each separate sheet of paper!*
- *Indicate on the first sheet the total number of papers you hand in.*
- *Take a photo of each paper you want to hand in, save them in a well readable format (preferably pdf).*
- *Then upload the file via the Assignment tool in the Nestor Exam page of this course.*
- *In case the previous two steps create problems then find another solution to send your well-readable results in time, e.g. by email to b.j.kooi@rug.nl.*

Mark for the exam = 1 + 9*((sum of total points scored)/(max. number of point (76)))

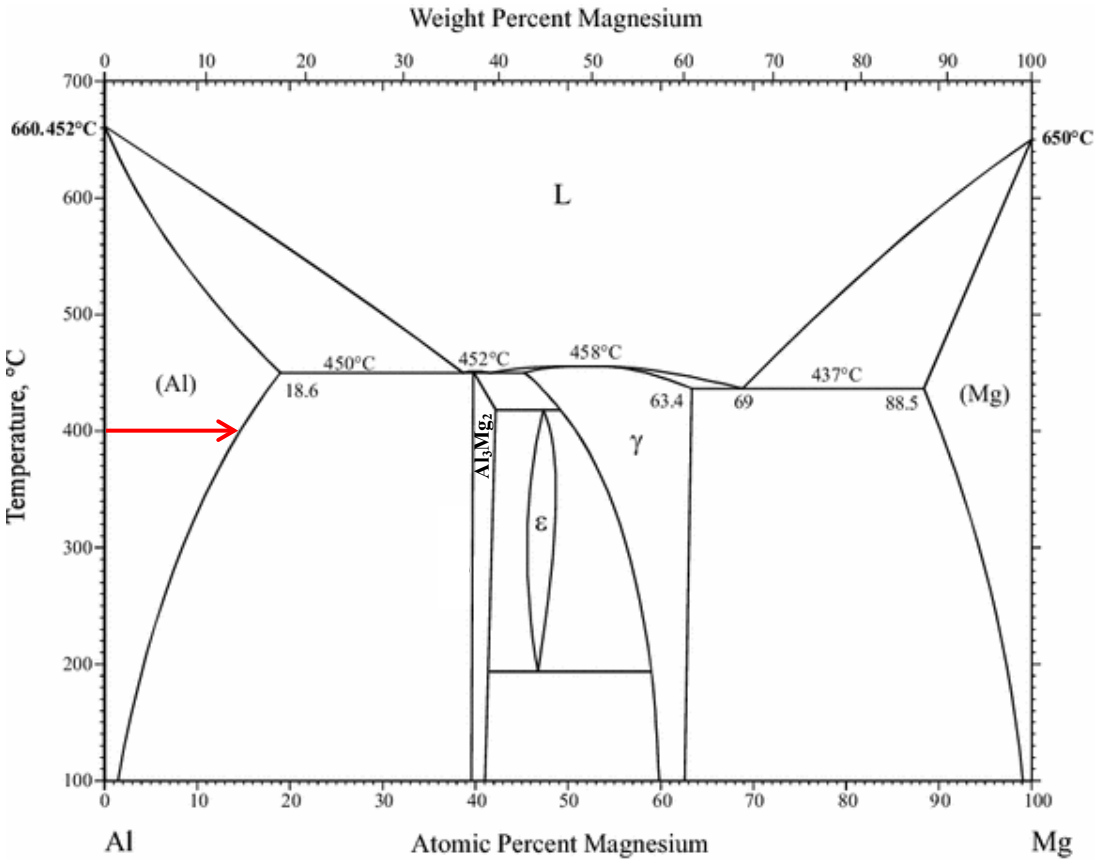
Suggestions:

- *Work fast and write down answers concisely.*
- *When you have difficulty to find an answer and to formulate it, do not keep on thinking (and looking for (internet) sources) for a long time, but move to the next question. Then, come back to this (skipped and unanswered) question later when you still have time.*

Five (5) exercises in total.

Exercise 1 (19 points)

In the figure below you see the Al-Mg equilibrium phase diagram. Pure solid Aluminium has a face centred cubic (FCC) structure with lattice constant at room temperature: $= 0.404\ nm$. Pure Magnesium crystallizes in a hexagonal close packed (HCP) structure with lattice parameters: $a = 0.320\ nm$ and $c = 0.520\ nm$. Mg atom is 12 % larger than Al atom.



a) The red arrow in the phase diagram crosses different compositions (from 0 to 14.5 at% Mg) at the same temperature 400 ºC. How would you characterize phase(s) present at this temperature, covering the whole composition range from the left to the right of this arrow? Please, give its (their) crystal structure(s) and determine if lattice parameter(s) will vary (increase, decrease, no change) with the composition change along the arrow. (3 pt)

b) Determine a temperature range of solid solubility of Al-Mg alloy with 5 at% of Al. How does this temperature range change with a further increase of Al amount in this alloy? Up to which composition and temperature can we increase the amount of Al and still observe only an equilibrium solid solution of Al in Mg phase? What will be the crystal structure of this phase? (3 pt)

c) We have Al-Mg alloy with 10 at% of Mg, very slowly cooled down from liquid to room temperature. From the binary diagram determine:
i) at which temperature liquid starts to solidify and what is the composition of this first solid phase; (2 pt)

ii) at which temperature the last drop of liquid is present and what is the composition of this liquid; (2 pt)

iii) which phases and in which proportion are present at a temperature of 100 ºC? (2 pt)

d) We would like to maximize the strength of this material via thermal treatment. Propose such treatment consisting of three steps: Isothermal Heating 1, Cooling and Isothermal Heating 2. Propose temperatures and suggest times for both heating steps and specify if cooling between them should be slow or fast. (3 pt)

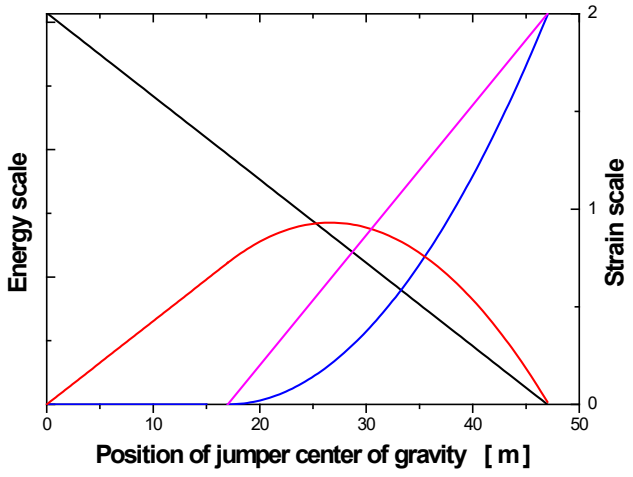
Describe by your own words the expected difference in microstructure of this alloy before and after thermal treatment. (2 pt)

Do you recommend a long time use of the strength of this material at temperatures around 200 ºC? Why? (2 pt)

Exercise 2 (15 points)

You are asked to design the core of bungee jumping rope made from **natural rubber** with Young's modulus E = 1.5 MPa, UTS = 28 MPa and being elastic until elongation of 600 %. Jumps will be performed from a bridge, which is 55 meters above the ground level. Jumps are considered to be save, when during a jump:
i) the heaviest allowed jumper's head down (mass 100 kg, height 2 m, with rope fixed on his ankles) will not approach the ground closer than 8 m and
ii) the rubber rope will not be strained more than 200 %.

(For simplicity we assume linear elasticity, which is not accurate for these large strains in the rubber and we also neglect the weight of the rubber rope, which in practice readily can be_15 kg.)



a) Let the zero of the coordinate system be located at the initial position of jumper gravity centre (56 m above the ground level) and jump length is measured from this point downwards the ground along the horizontal axis. In the above sketch there is a graph of four important physical quantities, calculated for the heaviest jumper from the moment of jump start until the moment of reaching the lowest jump point. These four quantities are:

- jumper potential **energy** U_p
- **strain** of the rubber rope ε
- elastic **energy** U_e accumulated in the rubber rope
- jumper kinetic **energy** U_k.

Associate the colour of each line within the graph with its appropriate quantity! (2 pt)

b) Using the fact that the maximum allowed strain is 200% for approaching the ground not closer than 8 m, calculate the idle (initial) length l_o of the rope. (2 pt)

c) This bungee jumping is a dynamic problem and therefore a bit difficult. However, when the 100 kg two meter tall person is hanging upside down in equilibrium (static) on the rope, his head is 28.5 m above the ground. Calculate the initial cross sectional area A_0 of the rope core. (3 pt)

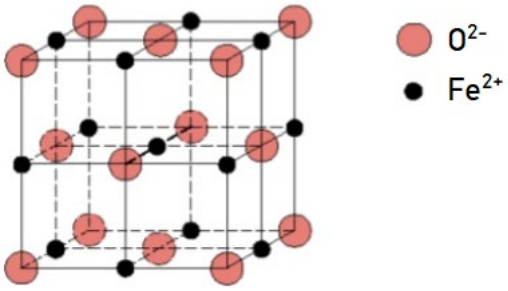
d) Natural rubber is available as a wire having a diameter of 4.4 mm. How many of these wires together are required to make the overall rope? What total length of rubber wire is required for making the rope? If you were not able to calculate l_o and A_o in previous questions, use values of 13 m and 1000 mm^2, respectively. (2 pt)

e) On the Internet and in the literature a bungee jump rope it often characterized by its spring constant: k [N/m], that characterize force required to elongate a particular rope by 1 m. Calculate the spring constant for the just designed rope (2 pt) and derive how spring constant k depends in general on rope geometry (A_o, l_o) and Young modulus E. (2 pt)

f) Estimate the safety coefficient comparing the maximal elastic stress (based on maximum strain of 200%) acting during the extremal jump with the UTS of the material used.(2 pt)

Exercise 3 (16 points)

One of the existing iron oxides is FeO, which has an FCC crystal structure with the rock salt symmetry, see the schematic on the right. The density of FeO is 5.74 g/cm^3. The molar mass of iron is 55.85 g/mol, the molar mass of oxygen is 16.0 g/mol and Avogadro's constant is 6.022x10^{23} 1/mol.



a) What is the ratio of Fe to O ions in FeO? Why? (1pt)

b) What is the coordination number and coordination geometry of FeO? (1pt)

c) Calculate the lattice parameter (unit cell edge length) of FeO. (3pt)

d) What are the theoretical stable extreme values (minimum and maximum) for the radii of the Fe^{2+} and O^{2-} ions? Use 0.430 nm as lattice parameter for FeO in case you did not find the solution to (c). (3pt)

e) We have a polymer that consists of a mixture of four types of molecules with molecular weights corresponding to 200, 400, 600, 800 times the monomer weight. The number fractions for the *first* two types are 0.40 and 0.30, respectively. The number average molecular weight is 400 (in terms of monomer weight). Calculate the number fractions for the *last* two types. (2 pt)

f) Now calculate the weight average molecular weight (in terms of monomer weight). (2 pt)

g) We have two (cylindrical) bars of natural rubber (poly-isoprene) with a length of 10 cm. One is vulcanized the other not. We load at room temperature both pieces parallel to their length for a few minutes to a total strain of 400% (which is about 80% of their fracture strain) and then take away the load. Estimate what length in centimeters both pieces have after the load is taken away. (2 pt)

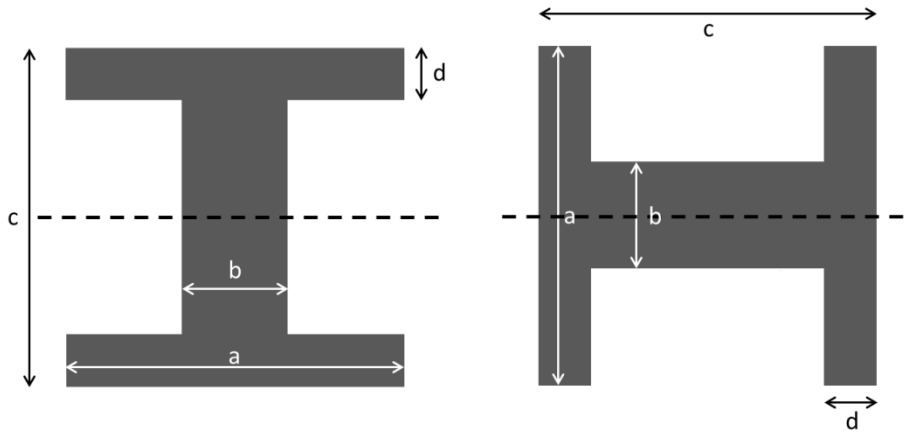
h) What happens if the whole experiment in the previous exercise is performed with the same loads below the glass transition temperature of the rubber? (2 pt)

Exercise 4 (10 points)

a) Explain why *the selection* of materials in mechanically loaded constructions can be affected by the shape of the materials. (3 pts)

b) Explain why in constructions that are loaded in bending and torsion materials should be shaped into *hollow rectangular* cross-sections for bending and *hollow circular* cross-sections for torsion. (3 pts)

c) The shape factor for bending is defined as $\phi_B^e = 4\pi I_{xx}/A^2$ with $I_{xx} = \int y^2 dA$ with y the distance to the bending axis. We have a long beam with as cross section a H or an I profile (with identical cross-sectional areas); see figure below. The bending axis is horizontal in the center of the profiles. Explain by proper qualitative reasoning which one of the two profiles has a larger shape factor and thus performs better in case of bending. For the I profile shown on the left write down (without solving it!!!) the appropriate integral $I_{xx} = \int y^2 dA$ with dA and the proper integration intervals in terms of the a, b, c and d dimensions as indicated in the figure. (4 pt.)



Exercise 5 (16 points)

a) Diamond has a very high Young's modulus of around 1050 GPa. Do you expect diamond to be a good or a poor thermal conductor? Motivate your answer in 1-2 sentences. (2 pt)
b) Lead has a low Young's modulus of around 14 GPa. Do you expect lead to be a good or a poor thermal conductor? Motivate your answer in 1-2 sentences. (2 pt)
c) The resistivity of a pure copper wire at 20 ^{o}C is 1.7 10^{-8} Ωm and of one containing 1 at.% nickel (and thus 99 at.% Cu) is 2.7 10^{-8} Ωm. When we increase the temperature from 20 ^{o}C to about 310 ^{o}C what resistivity value you expect for each of the two wires? Show how you determine the values. (3 pt)
d) When we shine visible light on a semiconductor its electrical resistivity can significantly change. This can be nicely used in sensors. Explain if the resistivity increases or decreases and explain why it changes. (2 pt)
e) Would you expect a difference in resistivity when we shine either blue (close to UV) or red (close to IR) light on the semiconductor? Explain your answer. (2 pt)
f) We have two samples of indium phosphide (InP, which belongs to the class of III-V semiconductors). Sample 1 is produced with perfect crystal structure and in sample 2 on average for each 10^{7} crystal unit cells (lattice parameter of the cell a_{InP}=0.586 nm) 1 In atom is replaced by 1 P atom. What type of semiconductor is sample 1 and what type is sample 2? Explain your answer (2 pt.)
g) The mobility of electrons μ_e=0.50 m^2/(Vs) and of holes μ_g=0.015 m^2/(Vs). The unit charge = 0.16 10^{-18} C. Compute the resistivity of sample 2 when it is in the extrinsic (exhaustion) regime. (3 pt.)