Exam Materials Science

## (Applied) Physics

January 27 2015, 9:00-12:00

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.

Mark for the exam = 1 + (sum of total points scored /8.5)

Suggestions:
- *When you have difficulty to find an answer and to formulate it, do not keep on thinking 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).*
- *Answer concisely: For all questions it is possible to write down the answers in not more than a few sentences.*

Exercise 1 (17 points)

Atomic percentage, magnesium

Al–Mg phase diagram
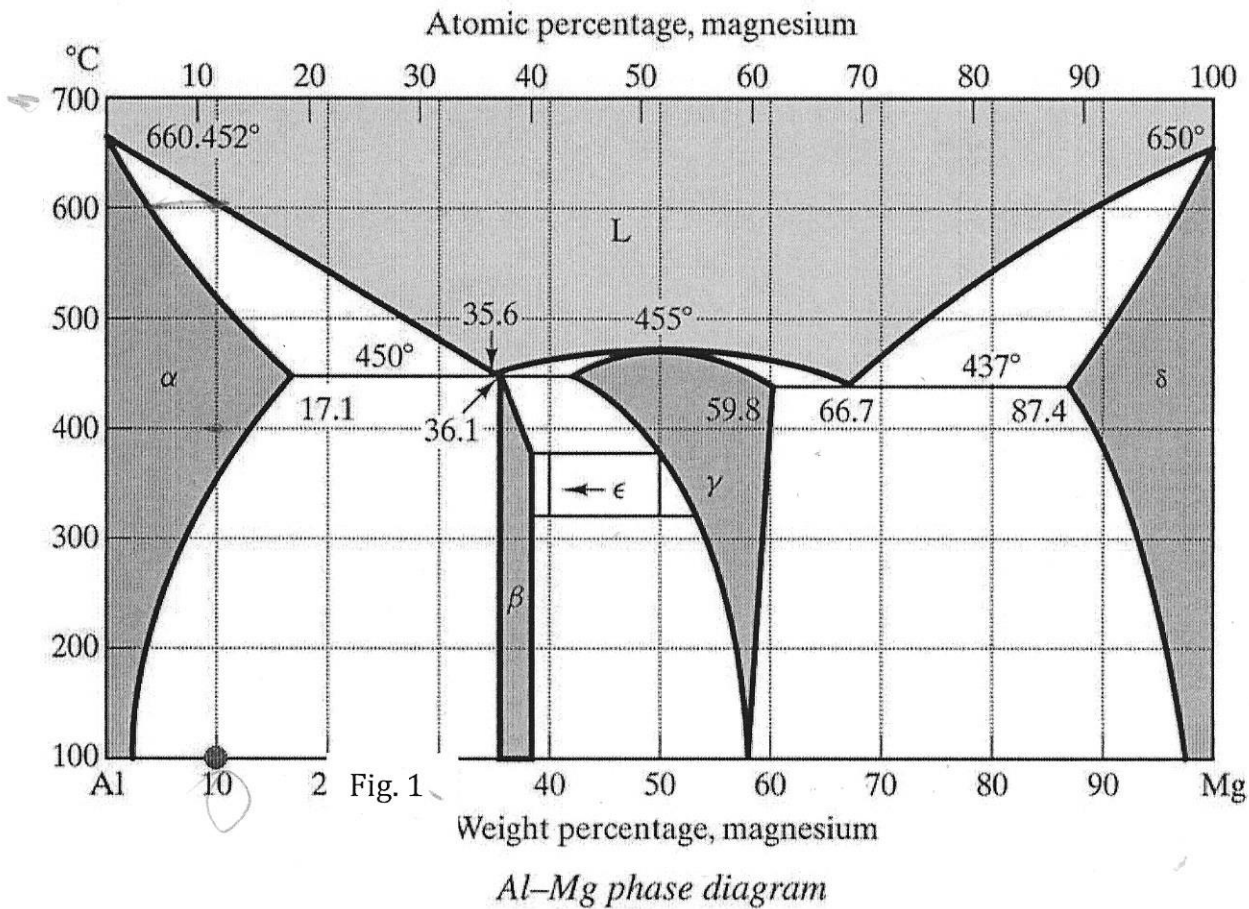
For aerospace applications aluminum alloys are popular construction materials, because of their excellent combination of mechanical properties and low density (weight). For the first part of this exercise (a-d) we consider an Al-Mg alloy with 10 weight-% Mg (see Fig.1).

a. This alloy is cooled down from 700 °C. At which temperature is the first solid phase formed (in the liquid)? What is the weight-% Mg in this first solid phase? (2 pt)

b. At which temperature will the last liquid disappear? What is the weight-% Mg in this last tiny bit of liquid? (2 pt)

c. Compute with the lever rule the fractions of the (various) phases that are present in this alloy with 10 wt-% Mg at 400 °C and 200 °C. Show how you obtain your answers. (3 pt)

d. What structure do you normally expect (instead of words you can also sketch it with proper indication of the phases!) in this alloy with 10 wt-% Mg after cooling to 100 °C? (2 pt)

e. The Al-Mg phase diagram shown above indicates that aluminum-rich alloy can be strengthened by two different methods. Describe concisely (but completely) these 2 methods, i.e. how the strengthening can be executed in practice and explain why the aluminum becomes harder and stronger. (4 pt)

f. Al(uminum) has a face centered cubic (fcc) crystal structure, Mg a close-packed hexagonal (cph) structure. Write down, using crystallographic notation, what are the close-packed planes and directions in both structures and how many independent combinations of close-packed planes and directions, i.e. slip systems are possible in both structures. (4 pt)

Exercise 2 (17 points)

A thin coating of TiC is deposited (with Chemical Vapour Deposition) at 700 °C on a steel substrate surface, with dimensions 0.200 x 0.200 m². Due to the difference in linear thermal

expansion coefficient of the film and the substrate, respectively $5 \cdot 10^{-6}$ K^{-1} and $12 \cdot 10^{-6}$ K^{-1}, stresses do arise in the film at room temperature (20 $^\circ$C). Approximately no significant stresses develop due to cooling in the steel. Then this material system is loaded in a construction in such a way that the edges of the square surface elongate 0.2 mm. The Young's Moduli of TiC and steel are 449 en 212 GPa, respectively and their Poisson ratio's are 0.19 and 0.29.

a. What could be useful reasons to coat steel with TiC? Mention at least two. (2 pt)
b. What value of (total) stress is present in the TiC film and what value in the steel? (5 pt)
c. Are the stresses that develop due to cooling in the film in general favourable or unfavourable? Motivate this choice. (2 pt)
d. The stresses in the steel are raised beyond its yield strength of 550 MPa. Explain what will happen in the steel on a microscopic scale. Discuss the role of planes and defects in the crystal (lattice) and the influence of grain boundaries. (3 pt)
e. Different modifications of steel are present. Steel plate in cold rolled and recrystallized condition and both present with 0.3 or 0.45 wt.% C. Which one of these 4 types of plate has the highest yield strength?; explain why. (2 pt)
f. Ceramics are always less ductile than metals. Why is this so? Explain why this has a large impact on the 'fracture toughness' (K_{Ic}) of metals and ceramics. (3 pt)

Exercise 3 (14 points)

a) Based on only carbon atoms different materials (i.e. where the atoms are packed in different structures) can be produced. Give the names of three different carbon-based materials/structures and shortly describe how the C atoms are packed (mutually coordinated) in these 3 structures. (3 pt.)
b) In ceramic materials, based on ions, the mutual coordination of the cations and anions is determined by their relative ion radii, rC and rA, respectively. Compute the *maximum* value of rC/rA that holds in case of a 2-fold surrounding of anions around cations. (3 pt.)

PVC has a monomer mass of 62.5 g/mol. A PVC polymer appears to have the following (simplified) distribution of molecular masses: 30000 g/mol occurs for 40% of the number of molecules, 40000 g/mol for 30%, 50000 g/mol for 20% and 60000 g/mol for 10% of the number of molecules.

c) What is the number average molecule weight (expressed in g/mol) of this PVC? (2 pt.)
d) What is the weight average molecule weight of this PVC? (2 pt.)
e) Natural Rubber or polyisoprene has its glass transition at –40 ºC. PVC has it at 100 ºC. Which of the two materials has a higher stiffness (Young's modulus) at room temperature? Give an estimate of the difference in Young's modulus. Give also estimates of the maximum (fracture) strains (%) that can be achieved at room temperature in polyisoprene and PVC. (4 pt.)

Exercise 4 (16 points)

a) The temperature dependence of the electrical conductivity is totally different for metals and semiconductors. Explain in a few sentences why this is the case, including at least factors as bandgap, number of free charge carriers, charge carrier mobility. (4 pt)
b) When we shine visible light on a semiconductor its electrical conductivity can significantly change. This can be nicely used in sensors. Explain if the conductivity increases or decreases and explain why the conductivity changes. (2 pt)
c) Titanium has a conductivity at room temperature of about 2.5×10^6 (Ωm)$^{-1}$. It is applied in an aircraft where it can become relatively hot: 475 ºC. Compute approximately the

conductivity of Ti at this temperature? Explain why this change in conductivity occurs. (3 pt.)

d) We have two samples of InP which are different types of 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 (see periodic table below). What type of semiconductor is sample 1 and what type is sample 2? Explain your answer (3 pt.)

e) The mobility of electrons μ_e=0.50 m²/(Vs) and of holes μ_g=0.015 m²/(Vs). The unit charge = 0.16 10^{-18} C. Compute the conducticity of sample 2 when it is in the extrinsic (exhaustion) regime. (4 pt.)

IUPAC Periodic Table of the Elements

Exercise 5 (13 points)

In the figure below a so-called Ashby map is shown, in which the *thermal conductivity* is plotted against the *thermal diffusivity*.

a. Which materials in the Ashby map provide the best thermal isolation of a refrigerator (which is continuously cooled and thus creates a steady-state condition)? Motivate your answer. (2 pt)

b. Which materials in the above Ashby map provide the best thermal isolation of a cooler box (that as a function of time will gradually heat)? Motivate your answer. (2 pt)

c. With an optimal design of an axis loaded in torsion not only the material properties are important, but also the shape of the cross section plays an important role (where the shape is uniform along the length of the axis). The twist (rotation angle caused by the torsion) θ in the axis is quantified by: θ=(Tl)/(GJ), with T the torque applied to the axis, l its length and G the shear modulus of the axis material (assume G=0.4E with E the Young's modulus). J is the angular momentum of the axis which is defined by: $J = \int r^2 dA$, with dA infinitesimal small area elements and r the distance of these elements with respect to the centre of rotation in the axis. The shape-factor is defined by: $\phi_T^e = 2\pi J/A^2$ with A the total area of the material in the cross section. Derive the 'performance'-function for the axis loaded in torsion with a variable shape-factor. The weight has to be minimized

(weight is thus the performance) and the requirement of the design is that the twist within the axis should not exceed the value θ_M for a torque T_a. (4 pt.)

d. 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 de bending axis. We have a H and an I profile (with identical cross-sectional areas); their cross sections are shown in the 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 (2 pt.)

e. Explain (e.g. by using one or a few examples comparing different materials) why shape factors have an important influence on the selection of the best materials that can be loaded safely by torsion or bending and where the design goal is to minimize weight (mass). (3 pt.)