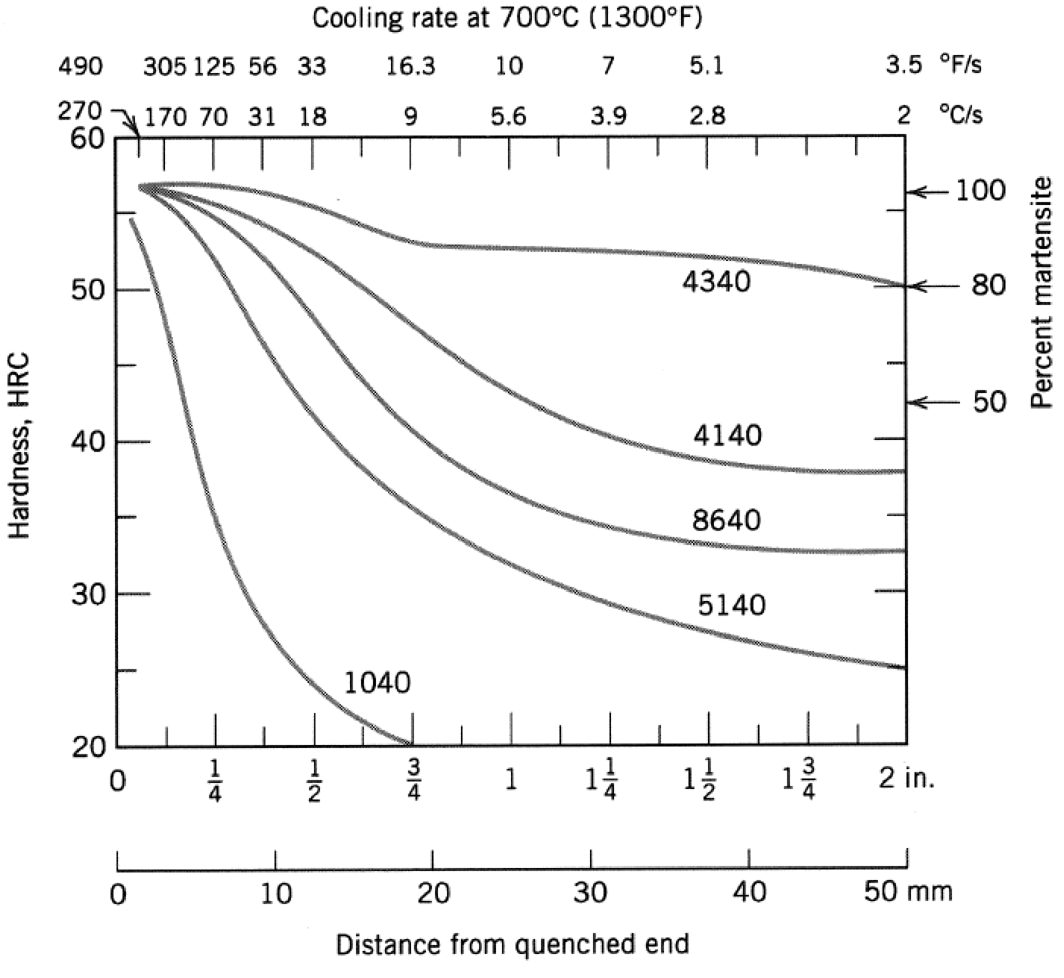
## QUESTION 1

The diffusion coefficients for iron in nickel are $9.4 \times 10^{-16}$ and $2.4 \times 10^{-14}$ $m^2/s$ at 1000°C and 1200°C, respectively. What is the magnitude of the diffusion coefficient at 800°C? (Hint: $D = D_o \exp\left(-\frac{Q_d}{RT}\right)$, and R = 8.31 J/mol-K.)

## QUESTION 2

The hardenability curves for a number of steels are shown in the diagram below. Rank the steels in ascending order according to their hardenability. If the thermal properties of the steels are the same, i.e. the cooling curves (temperature versus time) at a certain distance from the quenching end are the same for all the steels, explain the difference in hardness at a distance of 30 mm from the quenched end between 5140 and 4340 by plotting schematically the C curves for each in the same continuous TTT (i.e. temperature-time-transformation) diagram and comparing the resulting microstructures.



## QUESTION 3

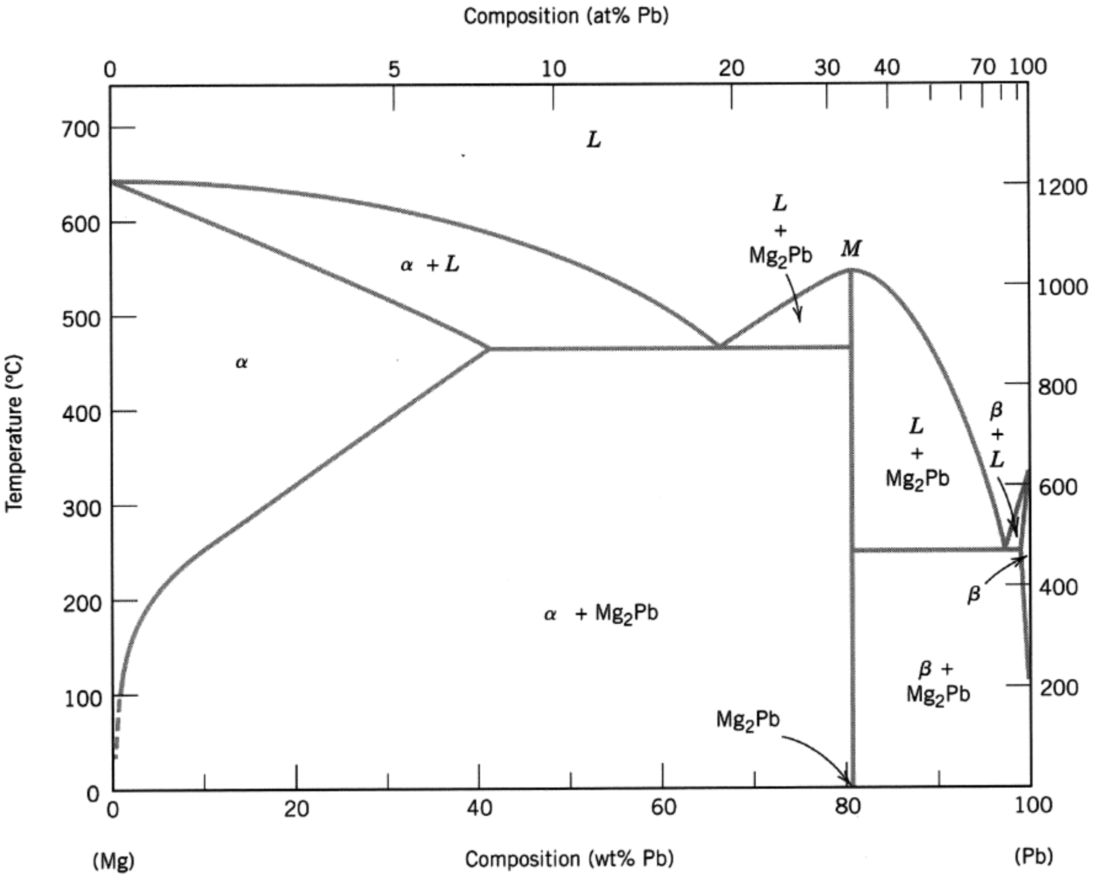
A magnesium-lead (Mg-Pb) alloy is slowly cooled (i.e. under equilibrium conditions) from 700°C. It is found by analysis that the first solid phase to solidify contains 20 wt% Pb. This alloy is further cooled to room temperature. Using the equilibrium Mg-Pb phase diagram below, answer the following questions.

(a) What is the composition of the alloy and what is the temperature at which the first solid phase solidifies? (Estimates rounding to convenient numbers are sufficient.)

(b) What is (are) the phase(s) present at room temperature and the mass fraction of each phase.

(c) Is there any eutectic structure present at room temperature? If so, what is the mass fraction of the eutectic structure? Is there any phase present at room temperature which is not the primary phase (the first solid phase that has solidified) and does not belong to the eutectic structure? If so, what is the mass fraction of this phase.

(d) Sketch the microstructure at room temperature.



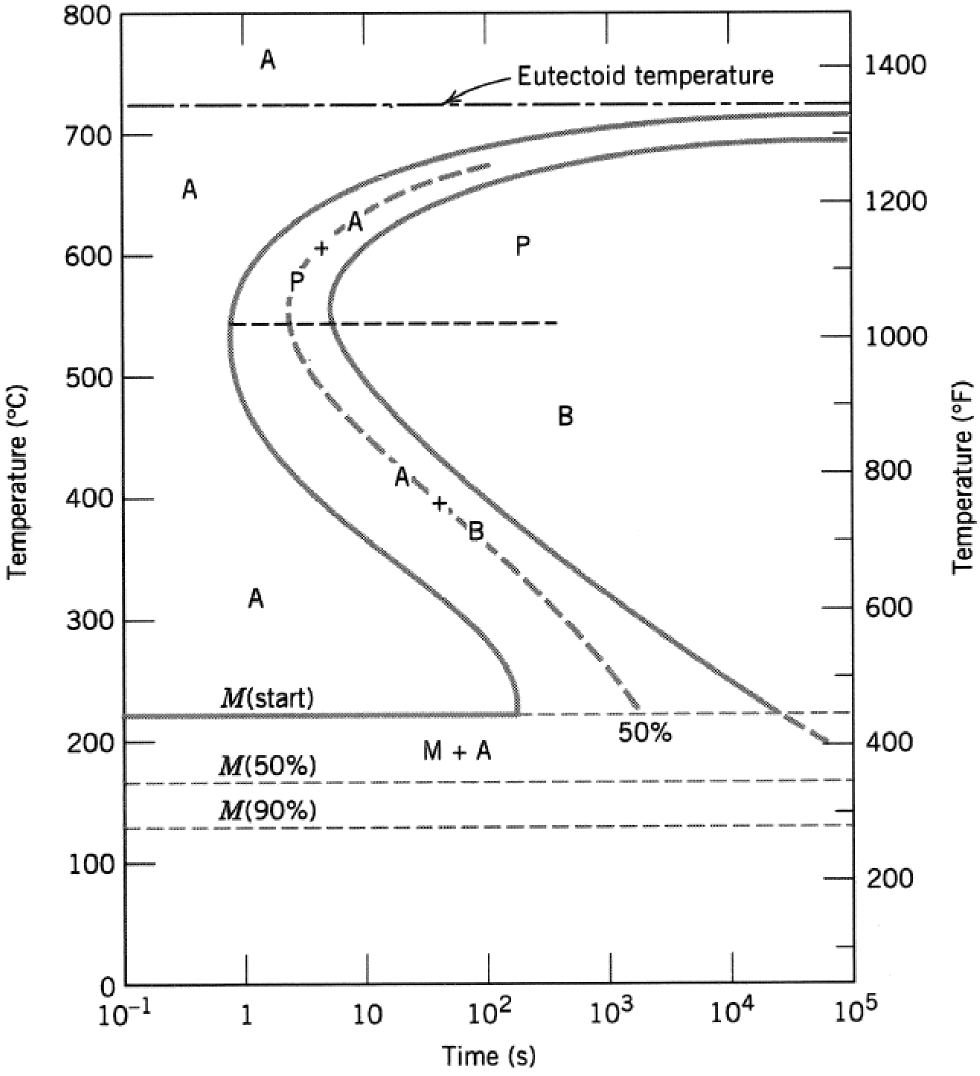
## QUESTION 4

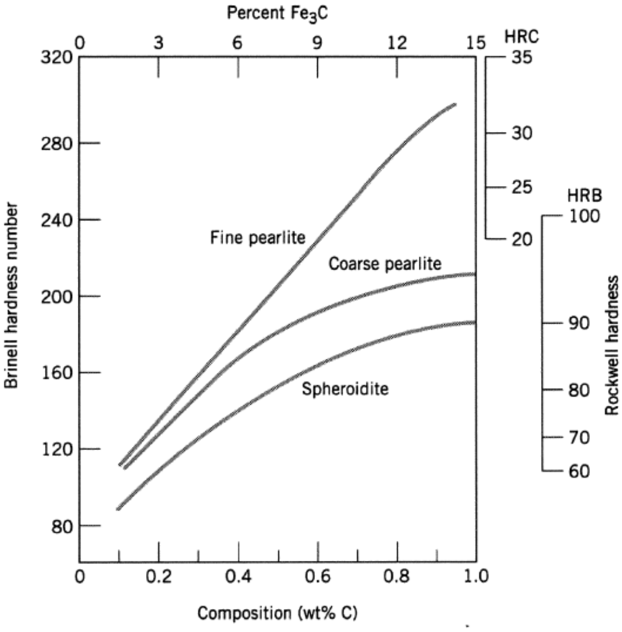
Using the isothermal transformation diagram for an iron-carbon alloy of eutectoid composition (0.76 wt% C) shown below and the mechanical properties versus carbon concentration diagrams shown on the next page if needed, perform the following tasks on a small specimen of the same composition.

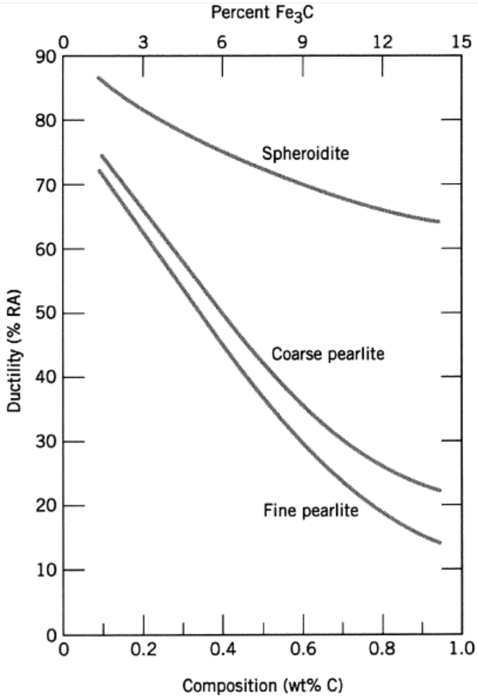
(a) Specify the heat treatment which will result in 50% fine pearlite, 25% bainite, 12.5% martensite and 12.5% tempered martensite. Plot schematically the heat treatment route on the diagram when applicable.

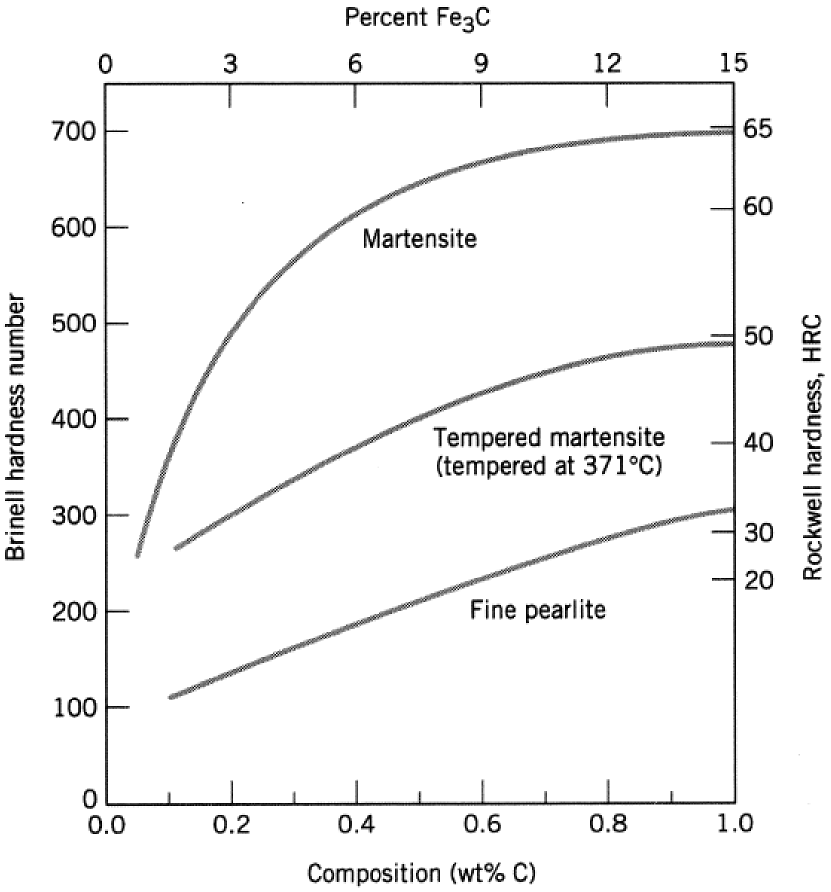
(b) Following the heat treatment steps below, what are the likely Brinell hardness number and ductility (in terms of reduction in area) of the resulting material? You are required to justify your answer and to sketch the resulting microstructure.

1. Hold at 750°C for sufficient time to obtain 100% austenite.
2. Quickly cool to 580°C and hold for 100 s.
3. Cool to room temperature.
4. Heat to 700°C and hold for 72 hours.
5. Cool to room temperature.




Percent Fe$_3$C
0
3
6
9
12
15
HRC
35
30
25
20
HRB
100
90
80
70
60
Rockwell hardness
Brinell hardness number
320
280
240
200
160
120
80
Fine pearlite
Coarse pearlite
Spheroidite
0
0.2
0.4
0.6
0.8
1.0
Composition (wt% C)


Percent Fe$_3$C
0
3
6
9
12
15
Ductility (% RA)
90
80
70
60
50
40
30
20
10
0
Spheroidite
Coarse pearlite
Fine pearlite
0
0.2
0.4
0.6
0.8
1.0
Composition (wt% C)


Percent Fe$_3$C
0
3
6
9
12
15
Brinell hardness number
700
600
500
400
300
200
100
0
Rockwell hardness, HRC
65
60
50
40
30
20
Martensite
Tempered martensite
(tempered at 371°C)
Fine pearlite
0.0
0.2
0.4
0.6
0.8
1.0
Composition (wt% C)

## QUESTION 5

(a) The values of the standard electrode potential for a number of reduction reactions are listed in Table 18.1 below. If a piece of Cu is connected to a piece of Zn, write the anodic and cathodic reactions, respectively. What is the equilibrium electrode potential difference between the two metals?

**(2 marks)**

(b) If both the anodic and cathodic reactions are controlled by activation polarisation, the overvoltages for the oxidation and reduction reactions can be expressed as

$$\eta_a \text{ (oxidation)} = \beta \log (i/i_o)$$

and

$$\eta_a \text{ (reduction)} = -\beta \log (i/i_o),$$

respectively, where $\beta$ and $i_o$ are positive constants for a particular half cell and $i$ is the current density. If the equilibrium potential (i. e. when the circuit is open) for a particular half cell is $V_o$, draw schematically the curves representing the potential as a function of log $(i/i_o)$ when the circuit is closed for both the oxidation and the reduction reactions. (Mark the axes and relevant quantities in the diagram clearly.)

**(3 marks)**

(c) Metal Sn can oxidise to form $SnO_2$. Do you expect the oxide layer formed on the surface to be protective? (The density of Sn is 7.30 g/cm$^3$ and the density of the oxide is 6.95 g/cm$^3$. The atomic weights of Sn and O are 118.7 and 16 g/mol, respectively.)

**(3 marks)**

## QUESTION 6

For the smelting production of aluminium

(a) Write the simple one-way chemical reaction for the formation of aluminium in a reduction cell and use the atomic masses of Al:27, O:16, C:12 to estimate (to one decimal place) the amounts of raw materials to produce 1t of aluminium, as well as the amount of $CO_2$ gas generated (ignore fluorides).

(b) How are the raw materials for this reaction introduced into the smelting process?

(c) The main impurity elements in aluminium (from the bauxite through the alumina) are Fe, Si & Ti. The main additional impurity from the smelting process is Na. H pick-up occurs during molten metal transfer and furnace operation. What options are there for Na removal prior to casting?

d) In what way are Na and H potentially detrimental to aluminium products?

## QUESTION 7

An audit of the melt quality, during a slab casting process, included measurement of the number of inclusion larger than 15 μm in thousands per kilogram, both before and after filtration, using a single phosphate-bonded ceramic foam filter tile with a pore size per inch of eighty (see the figure below).

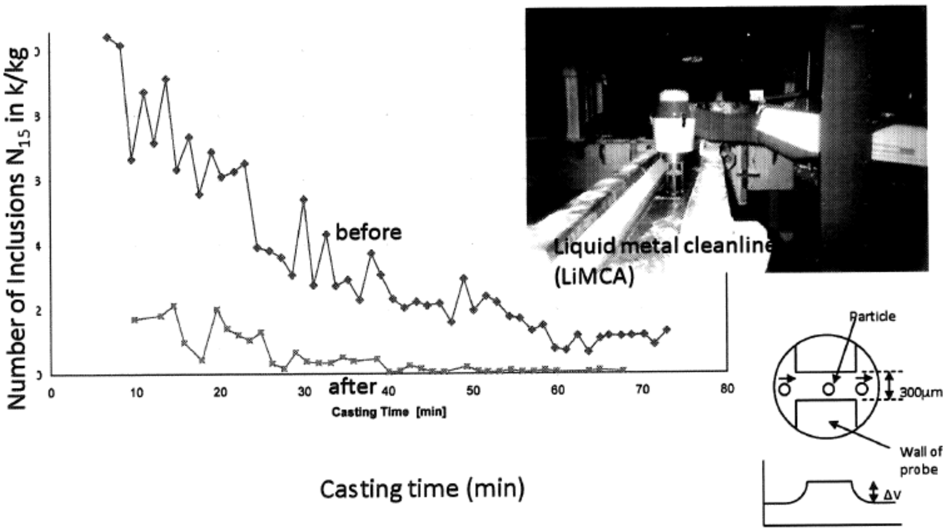
(a) Explain briefly how a CFF removes inclusions.

(b) What are some likely inclusion types being removed and their source?

(c) From the figure, estimate the inclusion removal efficiency of the filter after about 10 min and 60 min of casting. Is this as expected? Why is the level of inclusions before the filter reducing?

(d) What options (process or equipment) are there for improving the quality of slab for more critical rolled products applications?

**(8 marks)**



*Source: John Courtney, MQP at ACHT'11, Melbourne, 2010*

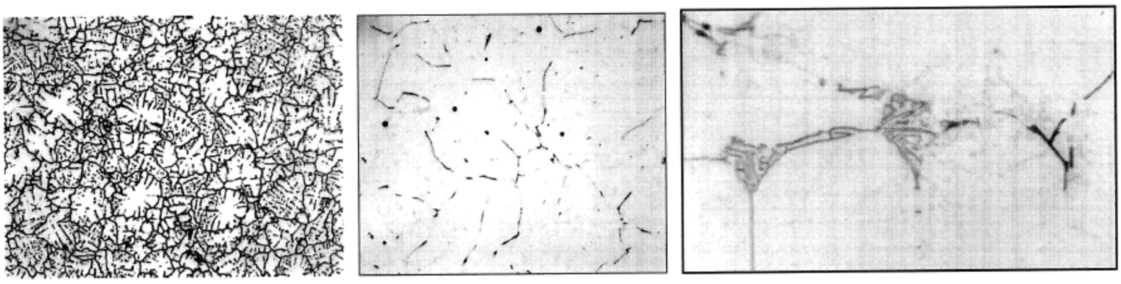
## QUESTION 8

Consider a 6063 Al alloy containing 0.5 wt% Mg, 0.4 wt% Si, 0.19 wt% Fe, and 0.04 wt% Mn. The as-cast solidification microstructure consists of Al (FCC) and small amounts of α-AlFeSi, β-AlFeSi, π-AlFeSiMg, $Mg_2Si$ and Si (see Figure ***a*** below for typical microstructures at various magnifications). An example composition analysis (SEM-EDS "spot" analyses) for a traverse across a cell or dendrite of the as-cast material is given in Figure ***b***. Following homogenization for 2h/570°C a comparable composition analysis is also shown in Figure ***b***. An equilibrium phase calculation for this alloy is shown in Figure ***c***.

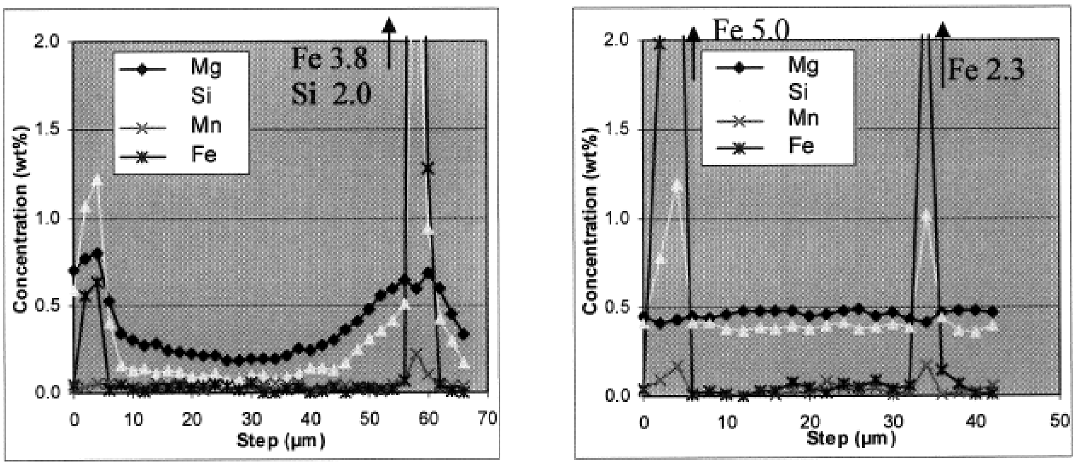
(a) Explain briefly the microstructural changes occurring during homogenization at 2h/570°C by reference to the figures.

(b) Identify the two intermetallic phases present in the homogenized material from the composition trace in ***b*** (for simplification, ignore the presence of Mn and use the table in Figure ***d*** to assist with identification).

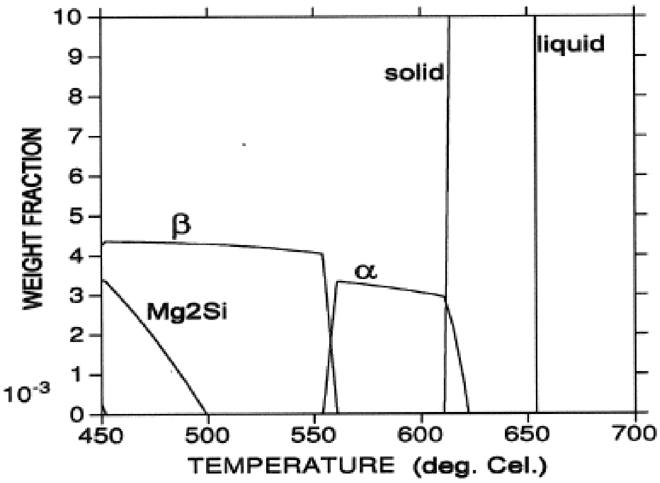
(c) Assuming the calculated phase diagram of Figure 2c is correct, has equilibrium been reached? What could be done to rectify this?



*a. As-cast microstructures at increasing magnification from left to right.*



*b. Composition measurement (SEM-EDS) of as-cast (left) and homogenized (right).*



*c. Calculated equilibrium amounts of phases.*

| Phase | Equilibrium Form | Atomic % | | Weight % | |
|---|---|---|---|---|---|
| | | Fe:Si ratio | Mg:Si ratio | Fe:Si ratio | Mg:Si ratio |
| α-AlFeSi | $Al_8Fe_2Si$ | 2:1 | - | 4.0:1 | - |
| β-AlFeSi | $Al_5FeSi$ | 1:1 | - | 2.0:1 | - |
| π-AlFeSiMg | $Al_8FeSi_6Mg_3$ | 1:6 | 1:2 | 0.3:1 | 0.6:1 |

*d. Intermetallic phases in the alloy.*

## QUESTION 9

Consider a 6xxx series Al-Mg-Si extrusion alloy. The alloy is precipitation strengthened by heat-treatment.

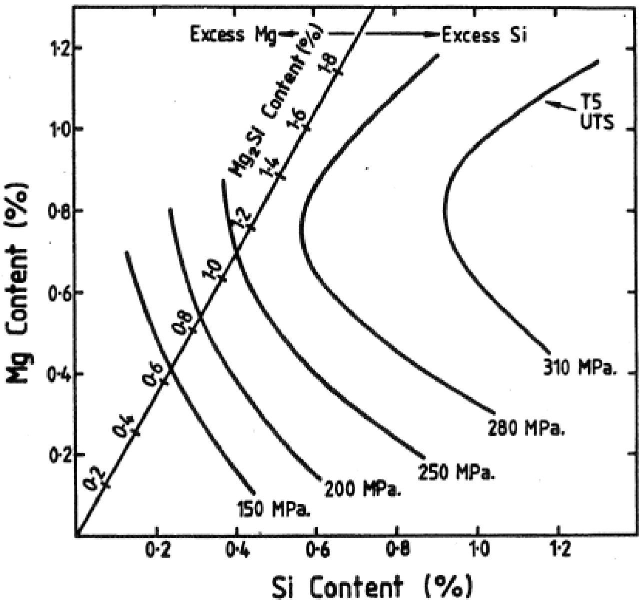
(a) Explain how the heat treatment process is integrated into the extrusion process.

(b) What metallurgical factors determine the temperature operating window for extrusion?

(c) Identify the minimum Mg & Si contents to achieve a tensile strength of 250 MPa according to the figure below.

(d) Why might an extruder choose this alloy over an alloy of composition Al-1.1 wt% $Mg_2Si$?

**(6 marks)**



*UTS (T5 tensile strength of Al-Mg-Si alloys)*

## QUESTION 10

Using the information in the table below (note: not all information is needed)

(a) What is the chemical formula of the following compounds: oxide of Ti, oxide of Al, oxide of Fe (give two alternatives), nitride of Al? Justify your formula based on the values in the table.

(b) The most common valence of C (4+) is associated with $CO_2$. However, many carbides form in which C behaves as an anion (consider SiC, TiC, $Al_3C_4$). By reference to the table explain how this comes about for these compounds and compare this with $CO_2$.

(c) Calculate the %ionic (versus covalent) nature of the bonding for SiC, ZnS and NaCl using the formula: $\%\text{ionic} = 100(1 - \exp[-0.25(X_{\text{cation}} - X_{\text{anion}})^2])$.

(d) Calculate the cation/anion ratio for NaCl and ZnS. Based on this alone, do you expect the two compounds to have the same structure?

(e) NaCl has an interpenetrating FCC structure of cations and anions with coordination number of 6 whilst ZnS has a structure where each atom has a coordination number of 4. How might this be explained from the data in the table?

| **Element** | **Atomic number** | **Most common valence*** | **Electronegativity** | **Ionic radius** |
|---|---|---|---|---|
| Li | 3 | 1+ | 1.0 | 0.78 |
| C | 6 | 4+ | 2.5 | - |
| N | 7 | 3- | 3.0 | - |
| O | 8 | 2- | 3.5 | 1.32 |
| F | 9 | 1- | 4.0 | 1.33 |
| Na | 11 | 1+ | 0.9 | 0.98 |
| Al | 13 | 3+ | 1.5 | 0.57 |
| Si | 14 | 4+ | 1.8 | 0.41 |
| S | 16 | 2- (or 6+) | 2.5 | 1.74 (or 0.34) |
| Cl | 17 | 1- | 3.0 | 1.81 |
| Ti | 22 | 4+ | 1.5 | 0.64 |
| Fe | 26 | 2+, 3+ | 1.8 | 0.83, 0.67 |
| Zn | 30 | 2+ | 1.6 | 0.83 |

* *Reference: Van Vlack, Materials Science for Engineers, 1975.*

## QUESTION 11

The survival probability of a ceramic material under uniform uniaxial tension can be expressed as

$$P_s = \exp\{-(\sigma/\sigma_0)^m\}$$

where $\sigma$ is the applied tensile stress, $m$ is the so-called Weibull modulus and $\sigma_0$ is a normalising parameter. If $m$ and $\sigma_0$ are constants and you have been given 30 tensile test specimens of the same volume of a ceramic material, write a procedure (step by step) for determining the Weibull modulus. How will the survival probability be affected if the real component has a greater volume than that of the test piece? Do you expect the survival probability to increase with time in service and why?

**(5 marks)**

## QUESTION 12

Define thermoplastic polymers and thermosetting polymers in terms of their structures, and describe their behaviours with increasing temperatures.

**(3 marks)**

## QUESTION 13

In a design assignment, you are asked to use continuous carbon fibres to reinforce an epoxy matrix to achieve Young's modulus of 250 GPa along the longitudinal direction of the composite. The epoxy matrix to use has a Young's modulus of 2 GPa and the continuous carbon fibres 400 GPa. If the allowed maximum loading of the C fibres is 60 vol%, is the design goal achievable? You are required to derive any equation needed in the calculation and state any assumptions made.

**(4 marks)**