MSE-422 - Advanced Metallurgy

Exam 24/01/2024

09h15 – 10h45

Family name:____

First name:____

No. Sciper:____

Question	**Points**
1	/15
2	/17
3	/13
4	/15
5	/15
Total:	**/75**
Grade:	

- Do not write more text than is necessary; sometimes, you can answer the questions with 1-2 words.
- You can also write on the backside of the sheets. If you do so, please indicate clearly to which question your answer belongs.
- If you need more paper for your answers, please ask.

1) Advanced steels (15P)

a) In Table 1, the chemical compositions of several steels are listed in wt.%. Their SEM images are respectively shown in Figure 1.

- Please complete the table by adding their EN steel name designation. (2P)

Table 1: Designations and compositions of four different steels;

Nr	Steel	C	Cr	Ni	Mn	Si	Mo	Al
1		0.61			24			
2		0.10			6	0.3		0.6
3		0.17			1.5	0.15		0.03
4		0.13	0.04	0.05	1.5	0.25	0.02	0.04

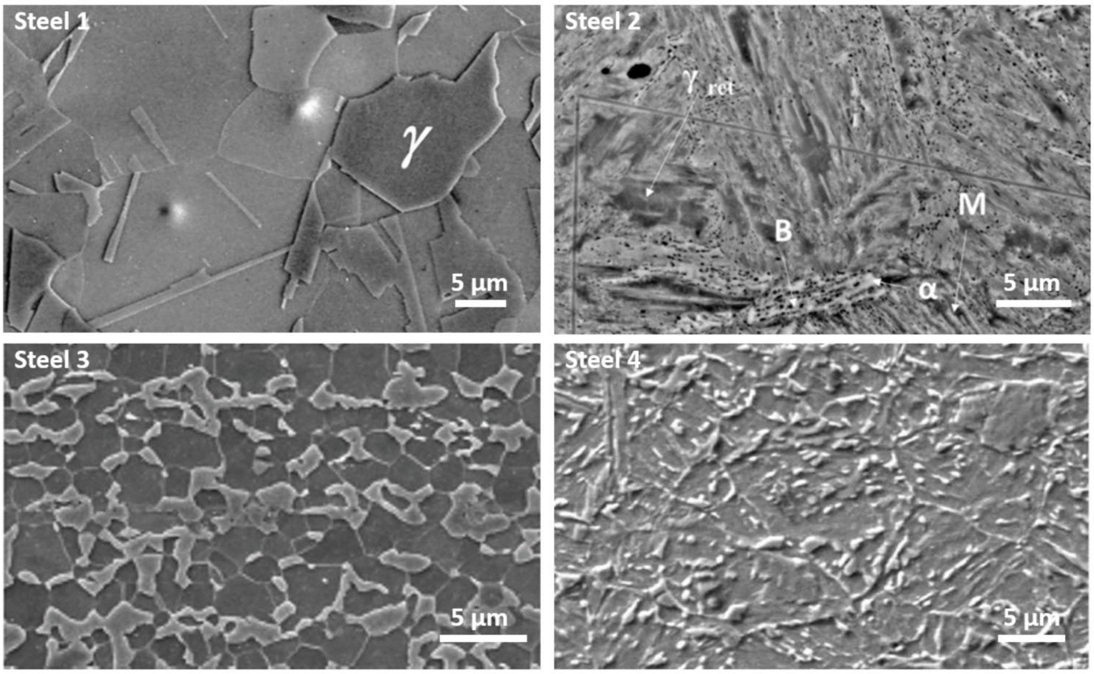

Figure 1. SEM images of steels 1-4;

- Associate the steel numbers in Table 1/Figure 1 to the following types of steels and justify your answer briefly: DP, CP, TRIP, and TWIP steels. (2P)

- The above-mentioned steels have different mechanical properties. Fill in the missing labels in Figure 2 using DP, CP, TRIP, and TWIP. (2P)

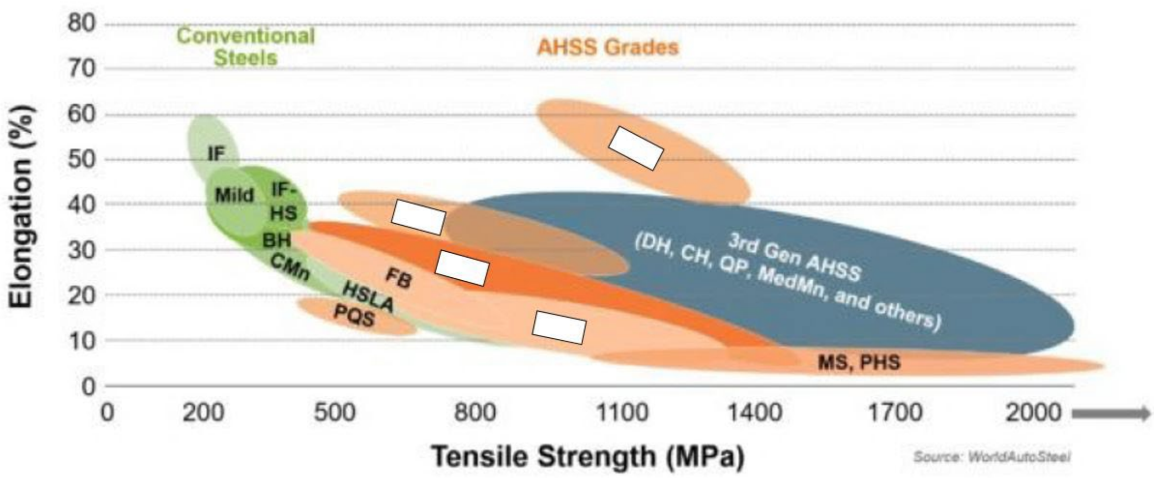

Figure 2. Comparison of mechanical properties of different steels;

b) Figure 3 demonstrates two heat treatment routes to obtain a DP steel (the volume fractions of the two phases are 70% and 30%).

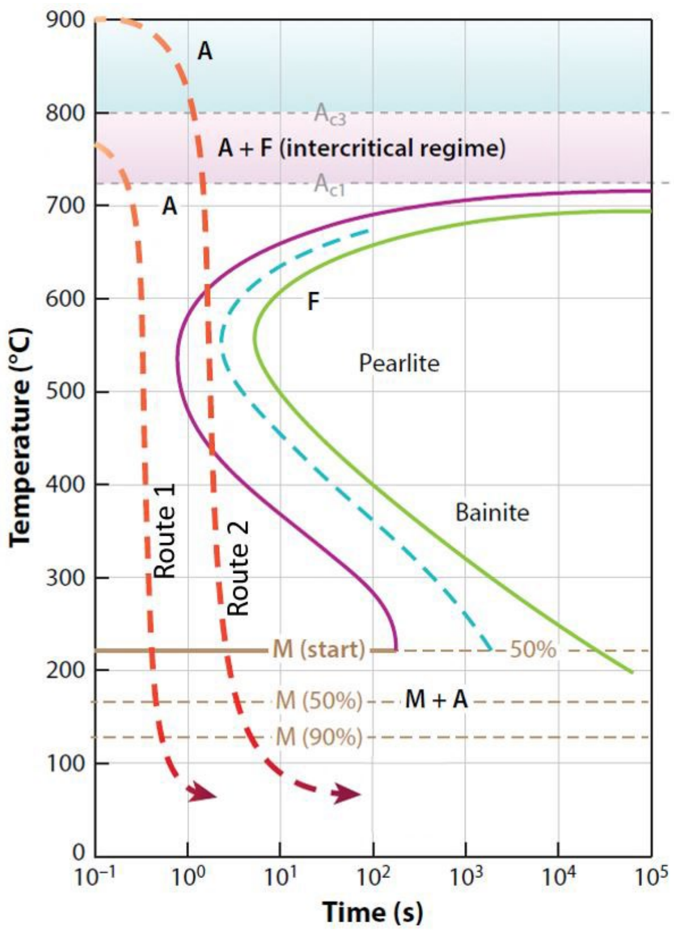

Figure 3. TTT diagram indicating the heat treatment methods of a DP steel;

- Describe the two routes then identify the initial and the final phases with their respective volume fractions. (2P)

- Briefly explain the physical meaning of temperatures A_{c1} and A_{c3}. (1P)

- How do the different phases in DP steels contribute to the mechanical properties? (1P)

c) Quenched and Partitioned (Q&P) steels belong to the 3rd generation AHSS. In general, Q&P steels have a composition of 1-1.5 wt.% Mn, 0.1-0.3 wt.% C, and 0-1.5 wt.% Al. Figure 4 demonstrates the heat treatment of a Q&P steel.

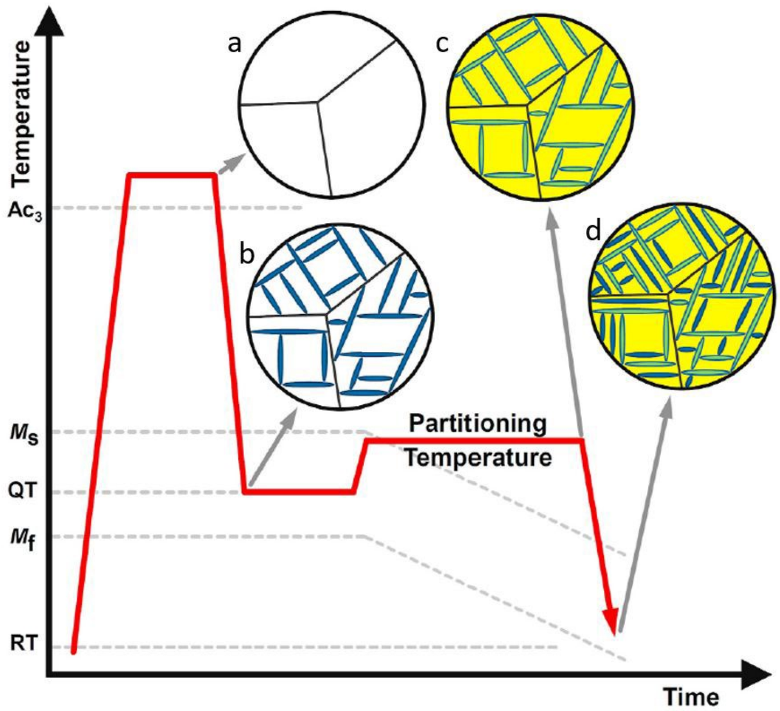

Figure 4. Schematic of the heat treatment process of a Q&P steel;

- What are the phases shown in the microstructures of a-d in Figure 4? Explain briefly what happened during the "partitioning" process. Why did the temperatures M_s and M_f decrease during partitioning? (3P)

- The volume fraction of the retained austenite at stage "d" in the above Q&P steel was observed to first increase and then decrease with increasing quench temperature (QT in Figure 4). Provide a possible explanation for this phenomenon. (2P)

2) Nickel and Titanium alloys (17P)

You recently joined an Aerospace company as a material expert and you are responsible for the selection, processing and characterization of high-performance Ni and Ti alloys

a) Your team leader gave you the following scanning electron micrograph (Figure 5), which shows the cross section of a single crystalline turbine blade of the alloy CMSX-4 after 1'000 h of service with a maximum temperature of 950°C in an aero-engine. The alloy has the composition (in wt.%) given in Table 2.

Table 2: Chemical composition of CMSX-4;

Ni	Cr	Co	Mo	Al	Ti	Ta	Hf	Re
Bal.	6.5	9	0.6	5.6	1.0	6.5	0.1	3.0

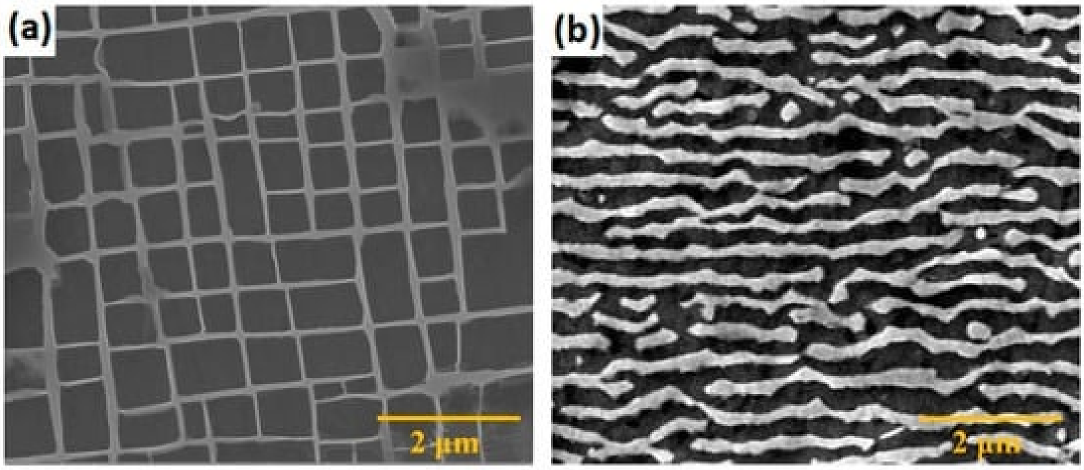

Figure 5. SEM – Cross section of a single-crystal turbine blade before and after 1'000 h of operation

- Explain the role of the alloying elements Cr and Re. (2P)

- Name the phases that can be seen in the micrograph (1P)

- Explain the microstructural changes that can be observed between the two micrographs. What is the common name for this phenomenon? (3P)

b) Your team leader shares the results from stress rupture tests performed at different test parameters on Ni-based super alloy used for turbine blades (shown in Figure 6). Consider that LMP = T (ln(t) + c) × 10^{-3} and that the Larson miller parameter constant c is 25.

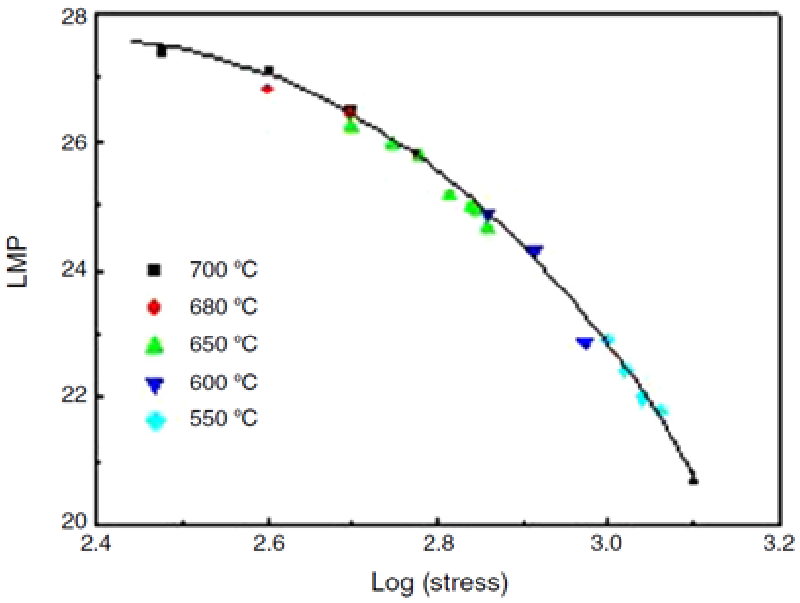

Figure 6. Larson Miller Parameter (LMP) correlation with stress obtained from stress rupture test of Ni-based super alloy.

- What stress can be applied so that the service life of the alloy at 500°C is 6000 h. (3P)

- Additionally, your team leader wishes to have a safety factor of 10% considering the testing uncertainty. What will be your suggested stress for application of the alloy at 500°C is 6000 h? (1P)

c) You are supposed to investigate the microstructure of a landing gear part of an airplane, which has been fabricated by Laser Powder Bed Fusion (LPBF) from the titanium alloy Ti-6Al-4V. LPBF is an additive manufacturing (or 3D-printing) process, in which a fine powder of the alloy is deposited layer by layer and then melted with a fast scanning high power laser (500W) to form parts with complex geometries. The laser spot diameter is typically around 100 µm and the laser scan velocities are on the order of 500-1000 m/s.

- What category of Ti alloys does Ti-6Al-4V belong to? (1P)

- Explain the role of V and Al. (1P)

- The EBSD map given in Figure 7 illustrates the microstructure of the part after the LPBF process. What is the name of the phase that has formed? Explain why this phase is pronounced after Laser Powder Bed Fusion. (2P)

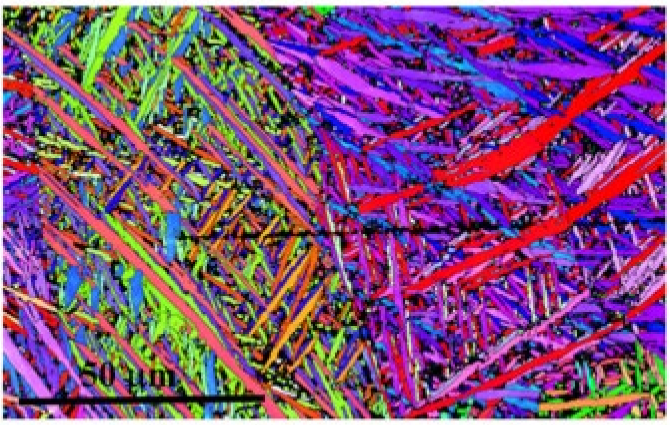

Figure 7. EBSD map of a Ti6Al4V alloy built after Laser Powder Bed Fusion

d) You heat treat the sample from question c at 1000 °C and then you cool it down to room temperature with
   i. furnace cooling and
   ii. quenching into water.

   What changes in the phases of the microstructure do you expect? How will these changes affect the ductility and the ultimate tensile strength of the alloy qualitatively? (3P)

3) Aluminium alloys (13P)

a) Consider two alloys with the following designation: AA6061-T6 and AA514.0. Based on this information, please name:

- The category of alloys these materials belong to. (1P)
- Their main alloying elements and the impact of these elements. (2P)
- What does the designation T6 stand for? (1P)

b) The figure below shows the binary Al-Ge phase diagram. Complete the phase diagram by adding the missing phases in each phase field. (2P)

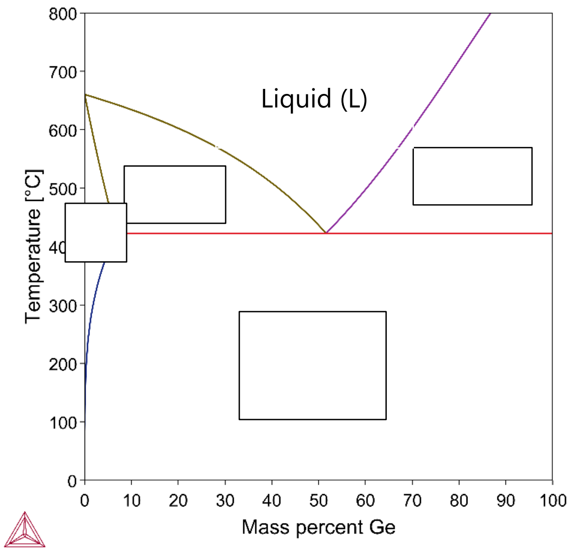

Figure 8. binary Al-Ge phase diagram

c) The figure below shows the EBSD grain orientation maps of an AA3003 alloy in the as-cast condition and one after hot rolling. Indicate which EBSD map (a or b) is attributed to the as-cast condition and which one to the hot-rolling and justify your answer. (1P)

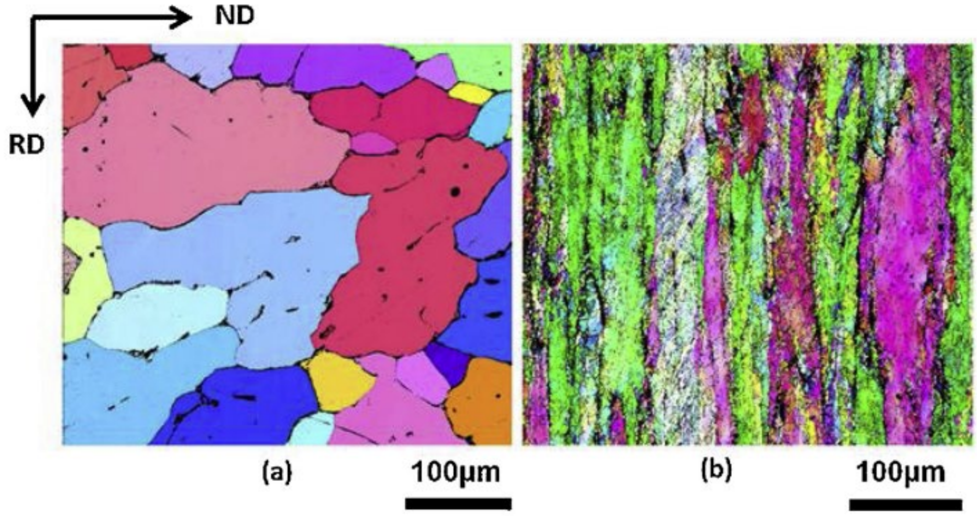

Figure 9. EBSD grain orientation maps of an AA3003

d) You have been given the heat treatment protocol for the alloy AA2017. Consider that two main phases are appearing in this alloy in the solid state (Al-FCC and Al_2Cu):

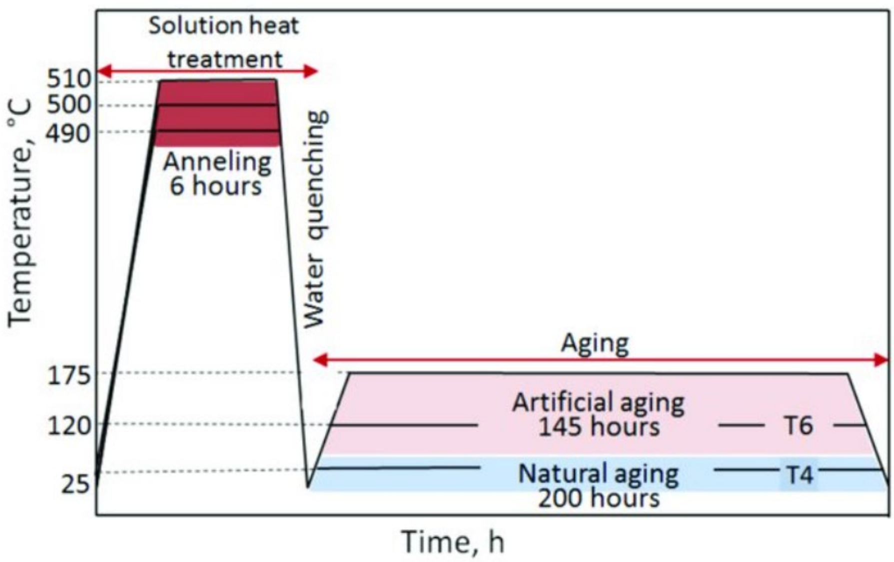

Figure 10. Heat treatment (T-t-profle) for AA2017

- Which phases appear in the microstructure after the solution treatment and which after the aging step. Justify your answer. (2P)

- Explain which strengthening mechanism is more important after the solution treatment step and which after the aging step. (2P)

- What impact would the increase of the temperature of artificial aging have on the hardness of the material, the number density and the size of the precipiates? Justify your answer. (2P)

4) High Entropy Alloys and Bulk Metallic Glasses (15P)

a) Calculate the entropy of mixing (S_{mix}) for an equimolar five-component HEA, FeCo-NiCrCu, knowing that the ideal gas constant is 8.3 J·K^{-1}·mol^{-1}. (1P)

b) Calculate the enthalpy of mixing (H_{mix}) for the above-mentioned HEA, assuming a constant interaction parameter Ω = 8 kJ ·mol^{-1}. (1P)

c) In reality, a HEA cannot achieve the ideal mixture. Therefore, a correction term, the excessive entropy (S_E), as a function of atomic packing and atom size is introduced for the entropy of mixing. S_E is negative and $|S_E|$ is positively related to the size mismatch of the atomic radii (δ). In fact, the entropy of mixing calculated in question a) represents the configurational entropy of mixing (S_C). In practice, the entropy of mixing is expressed as: $S_{\text{mix}} = S_C + S_E$.
A dimensionless thermodynamic parameter has been proposed for the design of HEAs:

$$\phi = \frac{S_C - \frac{H_{\text{mix}}}{T_m}}{|S_E|}$$

Knowing that the average melting point, T_m, of the five components in HEA FeCoNiCrCu is 1450 °C and $|S_E|$ is 0.031 J·K^{-1}·mol^{-1}, calculate the ϕ parameter for this HEA. (1P)

d) Al has been added to the equimolar HEA FeCoNiCrCu. With increasing content of Al, the valence electron concentration (VEC) is reduced. The VEC values of Fe, Co, Ni, Cr, Cu, and Al are 8, 9, 10, 6, 11, and 3, respectively. Assuming the second phase starts to form in this FeCoNiCrCu + Al system when its VEC = 8.1, calculate the molar fraction of Al at this critical point. What are the lattice structures of the primary phase and the second phase? (2P)

e) Calculate the configurational entropy of mixing (S_C) and the enthalpy of mixing (H_{mix}) for the FeCoNiCrCu + Al system with critical Al content mentioned in d), assuming a constant interaction parameter Ω_{Al} = -50 kJ ·mol^{-1} between Al and other elements and a constant interaction parameter Ω = 8 kJ ·mol^{-1} between Fe, Co, Ni, Cr, and Cu. (2P)

f) Knowing that the melting point of Al is 660 °C and the excessive entropy (S_E) of this critical system is 0.83 J·K^{-1}·mol^{-1}, calculate its ϕ parameter. According to previous research, this ϕ value is very close to the critical value to distinguish single-phase HEA and multiphase HEA. Do you expect higher or lower |ϕ| values for BMGs compared to HEA FeCoNiCrCu? Justify your answer briefly. (2P)

g) Explain the "confusion principle" for bulk metallic glasses (BMG) along with the Turnbull criterion (2P).

h) Explain two different fabrication routes for BMGs with a schematic. (2P)

i) Explain the plastic deformation mechanism of BMGs (2P).

5) Process Metallurgy (15P)

Steel and aluminium are key materials in the global economy and modern civilization, serving as the backbone of infrastructure, energy, industry, manufacturing, safety, and transportation systems. More than 1'900 Mt of steel and 100 Mt of aluminum are currently produced per year. Both metals are obtained from their metal ores, mainly hematite (Fe_2O_3) and Bauxite (Al_2O_3).

NOTE: you may use the Ellingham diagram on the last page for answering the questions below

a) The most relevant process for steelmaking is the blast furnace + oxygen converter process. In the blast furnace, hematite is reduced according to the following net reaction:

$$Fe_2O_3 + 6CO = 2Fe + 3CO_2 + 3CO$$

Coke containing 96.5% C is used to produce CO by combustion with air at the bottom of the furnace. Of the coke charged, 92.5% are burnt to CO.

- Calculate the mass of coke required to produce one batch of 5t of crude iron (2P)

- Calculate the mass of the CO_2 resulting from the production of 5t of crude iron (2P)

b) What is the role of lime (CaO) and/or lime stone ($CaCO_3$) in the blast furnace process? (1P)

c) In the recent years, the HYBRIT direct reduction process, in which hydrogen is used as the reducing agent, has been developed by the Swedish steel manufacturer SSAB

- Re-write the chemical reaction above assuming that pure hydrogen gas is used for the reduction of hematite. (1P)

- Name two advantages of the HYBRIT process in comparison with the conventional blast furnace process (2P)

d) The most relevant process for aluminium-making is the Hall-Héroult process, in which Bauxite is converted into pure Al in an electrochemical process.

- Explain why Al_2O_3 is mixed with cryolite Na_3AlF_6 in the process. (1P)

- Explain the difficulties with the direct reduction of Al_2O_3 (i.e. not in an electrochemical process) that would occur if Coke would be used as the reacting agent, similar to the steelmaking process, according to the reaction $Al_2O_3(s) + 3C(s) = 2Al(s) + 3CO(g)$ (2P)

- Explain why the use of recycled Al scrap is a good solution for fast decarburization of this sector. (2P)

- Aluminothermic welding, in which Al powder is mixed with hematite (Fe_2O_3) and ignited with a heat source, is used for e.g. welding of railway tracks without using electric power supplies. Briefly explain with a chemical reaction and the use of the Ellingham diagram what is happening in this process and why. (2P)

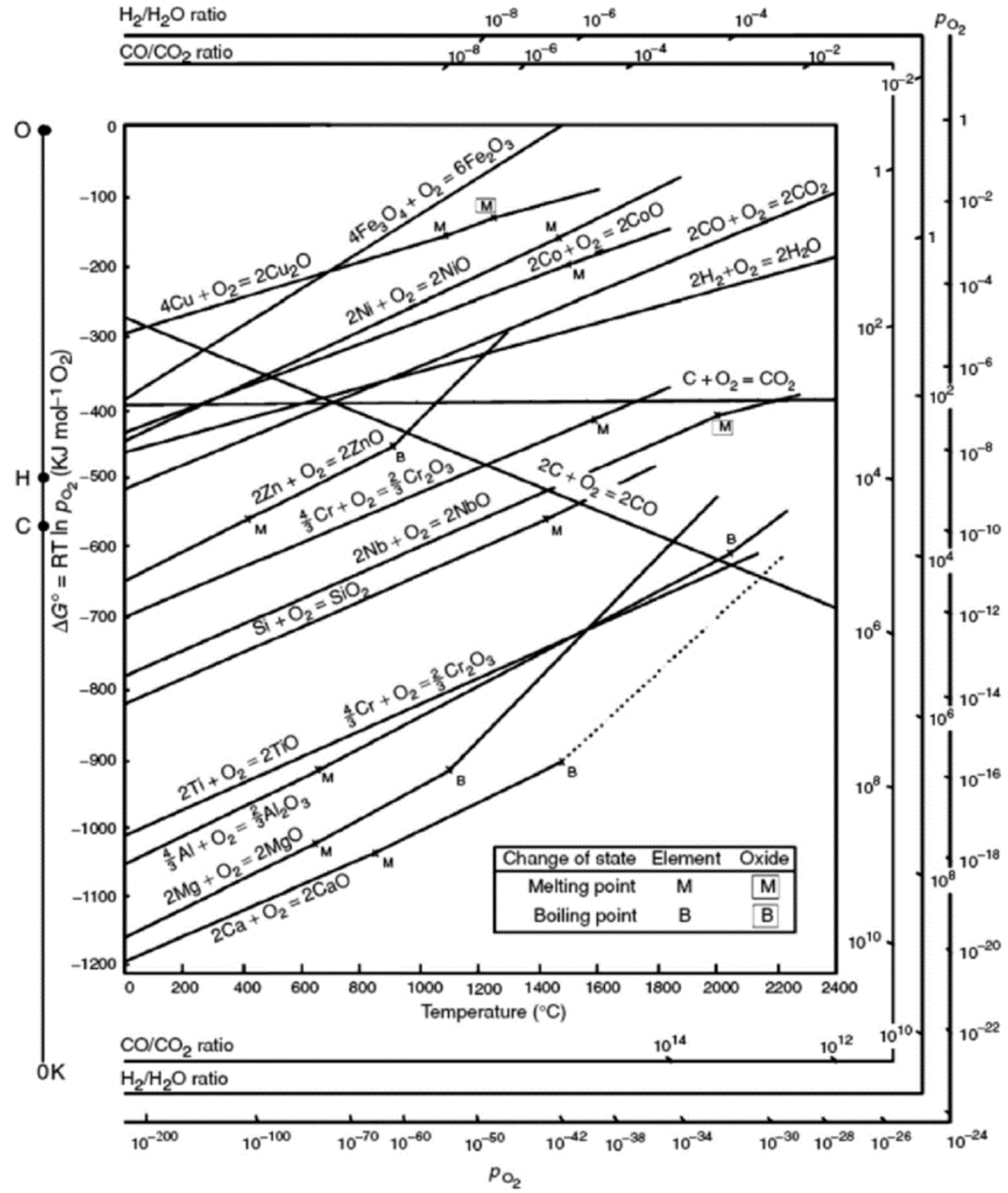

Figure 11. Ellingham diagram