

MSE-422 - Advanced Metallurgy**Exam 22/01/2025****09h15 – 10h45**

Family name: _____

First name: _____

No. Sciper: _____

Question	Points
1	/16
2	/15
3	/15
4	/15
5	/14
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) Basic Knowledge (multiple-choice and single-choice questions)

- Which of the following elements act as austenite stabilizers in steels (1P)?

A. Cr B. Ni C. Mn D. Mo

BC

- Which two of the following mechanisms are the most effective for strengthening steels at elevated temperatures (1P)?

A. Grain boundary strengthening B. Dislocation strengthening
C. Particle strengthening D. Solid solution strengthening

CD

- Which steel is most suitable for applications in tubing and piping systems of steam plants (1P)?

A. X20CrMoV 12-1
B. X3CrNiMoN 17-13
C. X3CrNiMo 13-4
D. X50MnCrV 20-14

A

b) Classification of Steels

- Given the following steel compositions, provide their European (EN) nomenclature (1.5P).

Composition A: 0.15 wt.% C, 1.5 wt.% Mn, 1 wt.% Si, 1 wt.% Al

15MnSiAl 6-4-10

Composition B: 0.02 wt.% C, 22 wt.% Cr, 5 wt.% Ni, 3 wt.% Mo

X2CrNiMo22-5-3

Composition C: 0.42 wt.% C, 1 wt.% Cr, 1 wt.% Mn, 0.2 wt.% Mo

42CrMnMo4-4-2

- Associate these compositions to the microstructures shown in Figure 1 (1.5P)

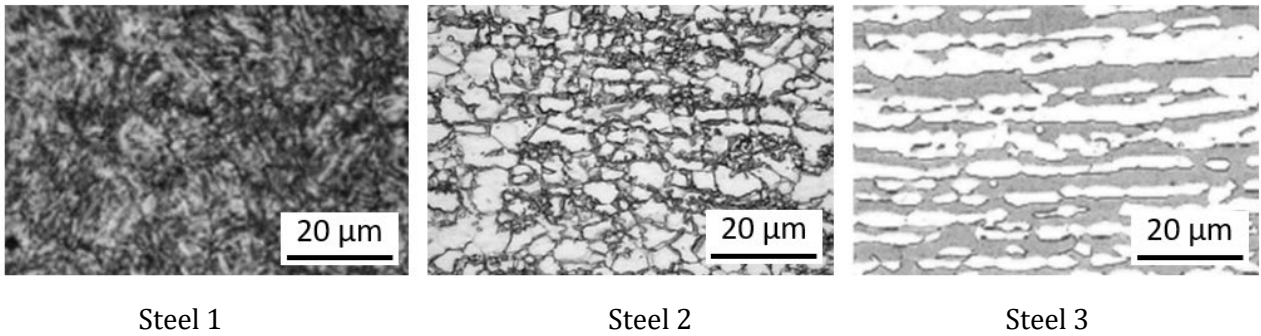


Figure 1. Microstructure of unknown steels

A-Steel 2, B-Steel 3, C-Steel 1

- Name the sub-classification of the steels shown in Figure 1 from the following options: DP, Duplex, CP, TRIP, TWIP, and Q&P steels (1.5P).

Steel 1-Q&P, Steel 2-TRIP, Steel 3-Duplex

- c) Figure 2 shows the temperature-time-diagram for a heat treatment (HT) of a 3rd generation AHSS containing 0.1 wt.% C, 6.5 wt.% Mn, 0.01 wt.% Si, and 0.01 wt.% Al. The dashed line is the only difference between the one-step HT and the two-step HT.

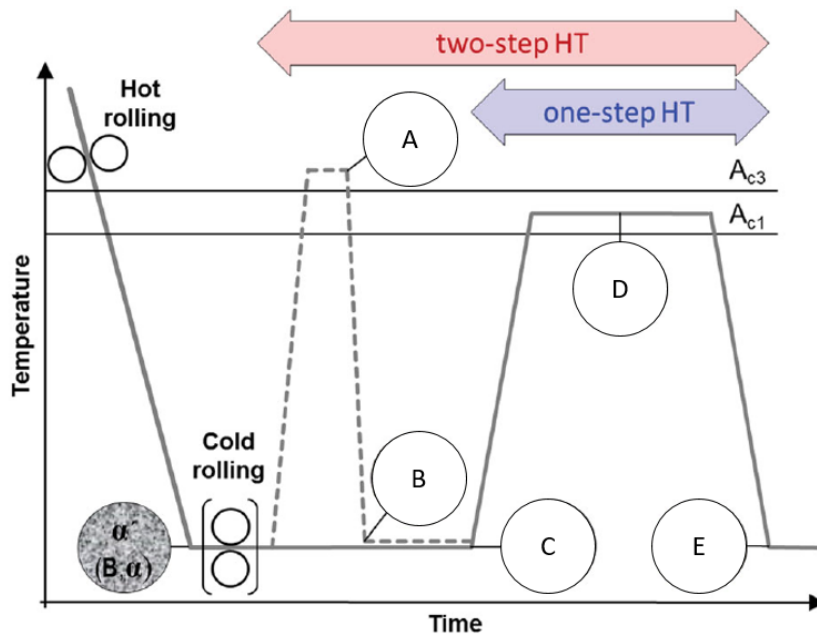


Figure 2. Illustrations of the one-step HT and the two-step HT routines.

- Describe the two HT processes and the evolution of phases of each (Resultant phases at C-E for one-step HT and A-E for two-step HT), then name the sub-classification of the obtained steel (2.5P).

One-step HT: C (deformed martensite, bainite, ferrite), intercritical annealing (C and Mn partitioning), D (ferrite, martensite, austenite), cooling, E (ferrite, tempered martensite, retained austenite)

Two-step HT: Austenitization, A (austenite), quenching, BC (martensite), intercritical annealing (C and Mn partitioning), D (ferrite, martensite, austenite), cooling, E (ferrite, tempered martensite, retained austenite)

medium-Mn TRIP steel

- Explain how the intercritical annealing temperature affects the formation and stability of retained austenite (2P).

Lower annealing temperatures enhances the stability of austenite, but the amount is limited.

Too high annealing temperatures reduce stability because of limited C and Mn partitioned from ferrite, leading to martensite transformation, reducing retained austenite.

- Compare the mechanical properties obtained with higher and lower cooling rates after the intercritical annealing and explain why (2P).

Higher cooling rates limit the diffusion, decrease the stability of austenite, leading to more martensite formation, therefore higher strength but lower ductility.

promote the stability of austenite by allowing more C and Mn diffusion and forming additional ferrite, therefore higher ductility but lower strength.

- Explain which of the two HTs generally results in better balance between strength and ductility and why (2P).

Two-step HT. Because the fine lath-shape structure of ferrite and thin-lamellar austenite is formed due to the nucleation of austenite from cementite along martensite laths (one-step HT leads to rather globular morphology).

2) Nickel Alloys (16P)

The alloys Inconel 738LC (IN-738LC), CMSX-2, and CMSX-4 represent three generations of Ni-based superalloys, widely used for turbine blades in stationary gas turbines. Their chemical compositions (in wt.%) are listed in Table 1. While IN-738LC is a conventionally cast alloy, CMSX-2 and CMSX-4 are first- and second-generation single-crystal superalloys, respectively.

Alloy	Generation	Elements (wt.%)											
		Ni	Cr	Co	Mo	W	Re	Al	Ti	Ta	Zr	B	C
IN-738LC	Conventionally cast	bal.	16	8.5	1.75	2.6	—	3.4	3.5	1.75	0.05	0.01	0.13
CMSX-2	1st generation SX	bal.	8	4.6	0.6	8	—	5.6	1	6	—	—	—
CMSX-4	2nd generation SX	bal.	6.5	9.6	0.6	6.4	3	5.6	1	6.5	—	—	—

Table 1: Chemical composition of Inconel 738LC, CMSX-2 and CMSX-4 (in wt.%)

Figure 3 shows the Larson-Miller plots of the three alloys. Consider a turbine blade operating under high-temperature and high-stress conditions.

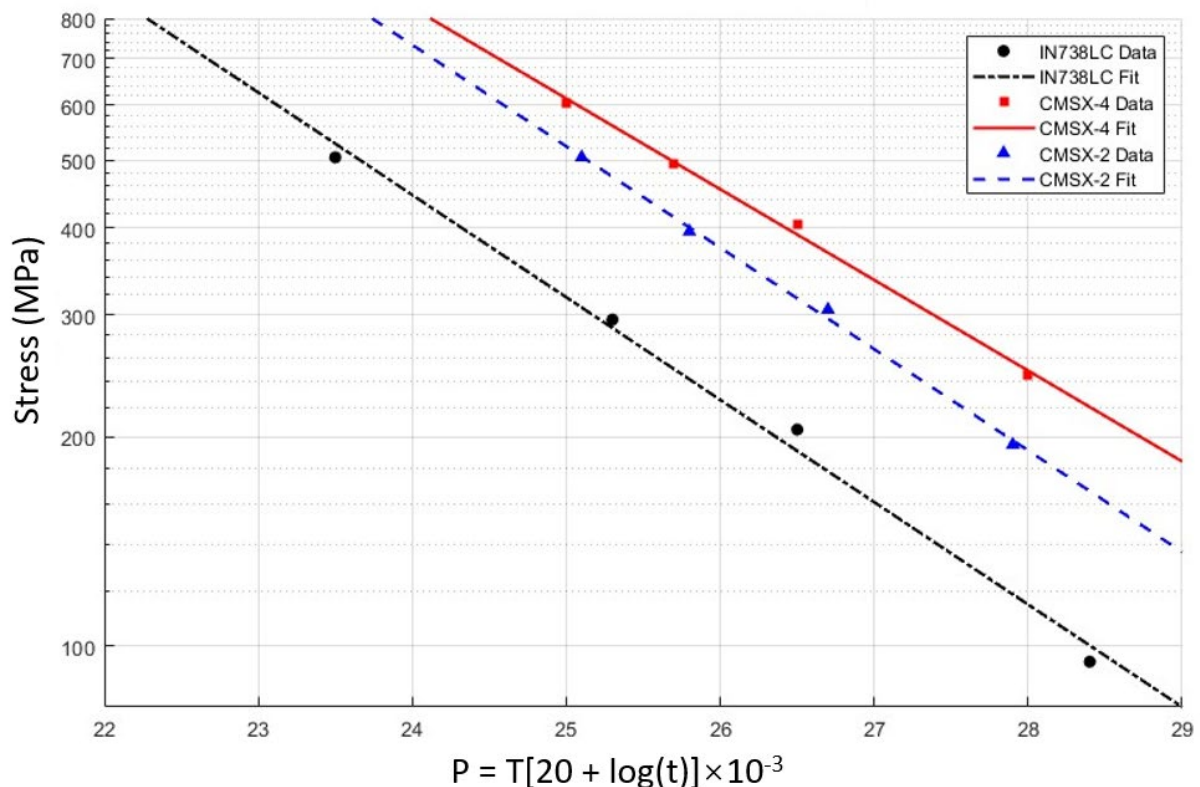


Figure 3. Larson-Miller diagrams of IN738-LC, CMSX-2 and CMSX-4

- a) Using the provided Larson-Miller plots,:
- Calculate the service life of the turbine blade at a stress of 300 MPa and a temperature of 850°C if it is made from IN738LC. (2P)

1. Service life calculation for IN738LC at 300 MPa and 850°C:

To calculate the service life of IN738LC, we use the Larson-Miller Parameter (P) formula:

$$P = T \times [20 + \log(t)] \times 10^{-3}$$

where T is the temperature in Kelvin (K) and t is the time in hours.

Rearranging the formula to solve for t (time in hours):

$$\log(t) = \frac{P}{T \times 10^{-3}} - 20$$

- Given $T = 850 + 273 = 1123$ K and $P = 25.2$ (from the plot at 300 MPa), substitute into the equation:

$$\log(t) = \frac{25.2}{1123 \times 10^{-3}} - 20$$

$$\log(t) = 22.44 - 20 = 2.44$$

- Solving for t :

$$t = 10^{2.44} \approx 275 \text{ hours}$$

Therefore, the service life of IN738LC under these conditions is approximately 275 hours

- Calculate the gain in service life if the blade is instead made from CMSX-4. (2P)

For CMSX-4, the Larson-Miller Parameter P is higher (approximately 27.3 from the plot). Using the same formula:

$$\log(t) = \frac{27.3}{1123 \times 10^{-3}} - 20$$

$$\log(t) = 24.31 - 20 = 4.31$$

- Solving for t :

$$t = 10^{4.31} \approx 20417 \text{ hours}$$

(Gain 20142 hours)

The service life of CMSX-4 under the same conditions is approximately 220417 hours

- b) What are the primary metallurgical and mechanical reasons for the significant difference in creep life between IN738LC and CMSX-4? Consider the role of alloying elements and microstructure (3P)
- CMSX-4 has higher Re and Ta content, improving solid solution strengthening, and stacking fault energy

- CMSX-4's single-crystal structure eliminates grain boundaries, reducing creep deformation mechanisms.
- c) Why are Zr, B, and C included in IN-738LC but absent in CMSX-2 and CMSX-4? (1P)
These elements strengthen grain boundaries, necessary in conventionally cast alloys like IN738LC. Single-crystal alloys do not require grain boundary strengthening
- d) Considering their chemical compositions, explain the increased creep performance of CMSX-4 in comparison with CMSX-2. (2P)
CMSX-4 contains rhenium, which increases solid solution strengthening, decreases SFE and enhances phase stability at high temperatures.

- e) Figure 4 shows a scanning electron micrograph of heat-treated IN-738LC with the typical γ - γ' microstructure.

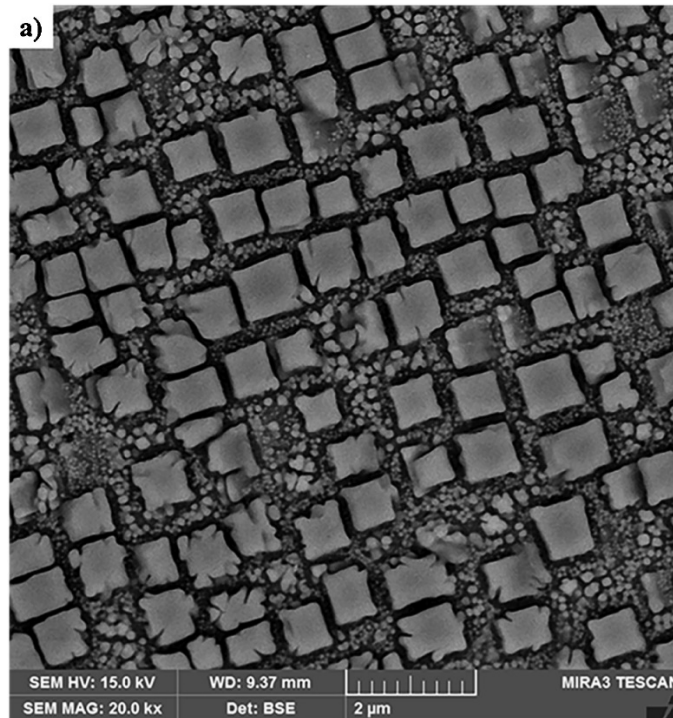


Figure 4. SEM – micrograph of IN-738LC after heat treatment

- Explain the terms "primary γ' " and "secondary γ' " precipitates in the context of IN-738LC. Discuss their roles in strengthening the alloy and indicate where they can be observed in the micrograph shown in Figure 4. (3P)
Primary γ' : Coarse, provide long-term creep resistance. Visible as larger particles in Figure 4.
Secondary γ' : Finer, strengthen against dislocation motion. Visible as smaller particles.
- Define the term "antiphase boundary" as it relates to the γ' phase in Ni-based superalloys. Explain how antiphase boundaries contribute to the strengthening mechanisms of these alloys. (2P)
Antiphase boundaries arise when dislocations cut through ordered γ' precipitates, requiring additional energy, thereby strengthening the alloy.

3) Titanium Alloys (15 P)

Commercially pure (cp-) Ti is used for biomedical applications such as bone plates or dental implant because of its combination of high corrosion resistance, biocompatibility and mechanical performance

- a) What is the main phase and its crystal structure in cp-Ti? (1P)
 α phase with HCP crystal structure.
- b) Explain the high corrosion resistance and biocompatibility of cp-Ti? (1P)
Excellent corrosion resistance and biocompatibility due to the formation of a stable 4-6 nm thick TiO₂ oxide layer;
- c) What are the main differences between the different grades of cp-Ti (grade1 – grade 4)? (2P)
Increasing amounts of Fe and O results in increasing strength, but decreasing ductility
- d) In implant production, it is necessary to mark implants with serial, batch, and company numbers, typically achieved through pulsed laser marking. Figure 5 shows a laser marked implant a) as well as the vicinity of a marked zone at higher magnification b)

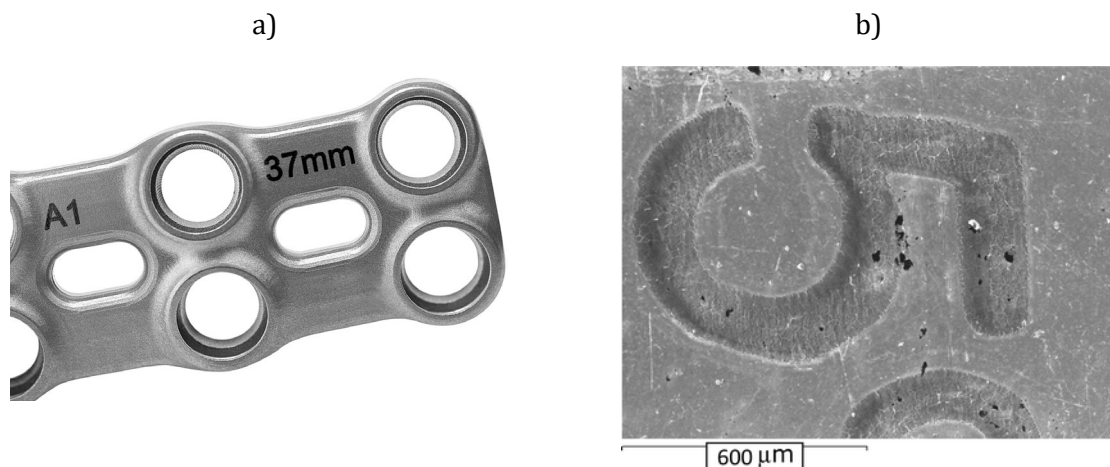


Figure 5. Laser-marked cp-Ti implant; a) bone plate; b) SEM of marked region

Fatigue samples made from cp-Ti Grade 3 were laser marked in an argon atmosphere, creating a branding zone approximately 1 mm thick. Fatigue tests were performed under tension-compression at a stress amplitude of 350 MPa on both marked and unmarked samples. The average number of cycles to failure, based on 5 tests, was 35'115 (\pm 1200) for unmarked samples and 24'447 (\pm 1348) for marked samples.

What could explain the observed differences in fatigue life between the marked and un-marked samples? Justify your answer. (2P)

- Laser marks are geometric notches. Cp-Ti has a high notch sensitivity because of its hcp crystal structure (less slip systems for accommodating local stress concentrations via plastic deformation)
- Laser marking can introduce microstructural damage (such as microcracks)

e) In the 1980s, the alloy Ti-6Al-7Nb was specifically developed for biomedical applications by the Swiss company Sulzer in Winterthur.

- Explain the role of the alloying elements Al and Nb (2P)
Al: Stabilizes α phase, increases strength.
Nb: Stabilizes β phase, improves ductility and corrosion resistance.

- Explain why Ti-6Al-7Nb is preferred over commercially pure titanium (cp-Ti) for permanent implants such as hip prostheses or spinal implants. (2P)

Superior strength, fatigue properties and wear resistance, essential for load-bearing applications like hip prostheses.

- Figure 6 shows optical micrographs of Ti-6Al-7Nb with different microstructures. Name and explain the microstructures shown (3P)

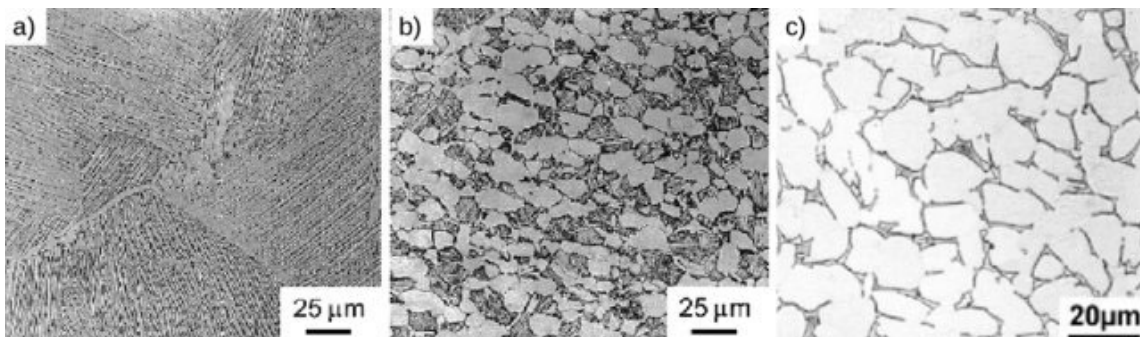


Figure 6. Optical micrograph- microstructures of Ti6Al7Nb after different thermos-mechanical treatments

- a) **Lamellar $\alpha+\beta$: α and β lamellae form upon slow cooling from β High toughness.**

- b) Bimodal $\alpha+\beta$: white regions α ,
- c) Equiaxed $\alpha+\beta$: white regions α , grey regions β Balanced strength and ductility.

- Which microstructure would you prefer for a permanent hip implant? Justify your answer (2P)

Equiaxed $\alpha+\beta$:

it provides an optimal balance of strength, ductility and resistance to crack initiation

Hip prostheses are not easily replaceable, so it is crucial to avoid fatigue crack initiation. For this reason, equiaxed microstructures are typically preferred. In contrast, for airplanes, crack lengths can be more easily measured and monitored. Fatigue crack propagation curves for Ti alloys are well-established, allowing parts to be replaced when necessary to ensure safety and reliability.

4) Intermetallics, High Entropy Alloys , Bulk Metallic Glasses (15P)

Titanium aluminides are a class of intermetallic compounds primarily composed of Ti and Al. These alloys exhibit a unique combination of properties, making them ideal for aerospace, automotive, and energy applications, particularly in components such as turbine blades, exhaust valves, and structural components

a) Figure 7 shows the binary Ti-Al phase diagram.

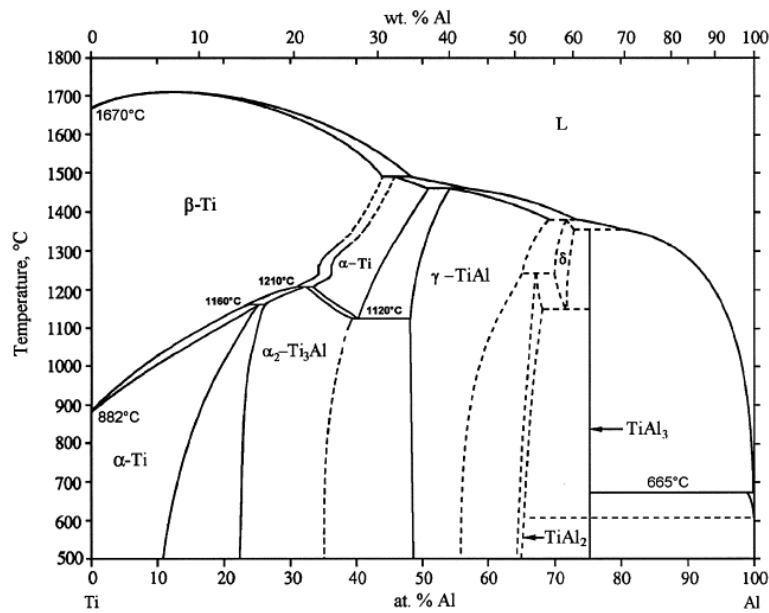


Figure 7. Binary Ti-Al phase diagram

- Indicate the compositional range of technical Ti aluminides. Which phases are formed? (2P)
45-50 at.% Al; phases: γ -TiAl, α_2 -Ti₃Al.
- Why are Ti aluminides preferred alloys for high-temperature aerospace applications? (2P)
Lightweight, excellent oxidation resistance, and high strength at elevated temperatures.

- Explain why Ti aluminides, despite their lightweight and strength, require alloying with Nb, Cr, or W for practical applications. (2P)
Enhances phase stability, ductility, and oxidation resistance.

- b) The table below shows the compositions of three different multi-component alloys in atomic %: a Bulk Metallic Glass (BMG), a High Entropy Alloy (HEA), and a conventional alloy. Indicate which composition corresponds to which alloy. (1.5P)

Composition	Alloy type
Ni40Cr25Fe18Mo5.5Co1.5W0.5	Conventional alloy
Hf20Mo15Nb25Ta25Ti25	HEA
Zr58Cu16Ni13Al10Nb3	BMG

- c) The formation of a single-phase solid solution in HEAs is governed by the Gibbs free energy equation:

$$\Delta G = \Delta H_{\text{mix}} - T\Delta S_{\text{conf}}$$

Where ΔG : Gibbs free energy; ΔH_{mix} : Enthalpy of mixing; T: Temperature; and ΔS_{conf} : Entropy of mixing (configurational entropy)

- Calculate ΔS_{mix} for an arbitrary equimolar five-element HEA at room temperature. How does the entropy change if the atomic fractions of the elements are unequal? (2P)

$\Delta S_{\text{mix}} = R \ln(5) = 13.38 \text{ J}/(\text{mol K})$. For unequal fractions, ΔS_{mix} decreases.

- Consider the role of ΔH_{mix} in determining the stability of HEAs. How does the magnitude and sign of ΔH_{mix} (positive vs. negative) influence the formation of solid solutions versus intermetallic phases? (2P)

Negative ΔH_{mix} favors solid solution formation; positive ΔH_{mix} promotes intermetallic phases.

d) Under which conditions can a high entropy alloy become a bulk metallic glass? (2P)

High cooling rate, multicomponent system with high ΔH_{mix} and low ΔS_{conf} .

e) A metallic glass alloy has the following properties: melting temperature (T_m) of 1200 K, glass transition temperature (T_g) of 800 K, thermal diffusivity (α) of $2.5 \times 10^{-6} \text{ m}^2/\text{s}$. Calculate the maximum critical cooling rate required for this alloy to be defined as bulk metallic glass (1.5P).

$$\sqrt{\alpha \frac{T_m - T_g}{R}} > 0.001 \text{ m}$$

$$R < 1000 \text{ K/s}$$

5) Aluminium alloys and aluminium processing (14P)

- a) Primary aluminum production is a critical industrial process that extracts aluminum metal from alumina (Al_2O_3) using the Hall-Héroult method. This process, while essential for producing large quantities of aluminum, comes with significant energy demands and environmental challenges.

- Explain the production of primary aluminum from Al_2O_3 in the Hall-Héroult process. (3P)

Setup: The Hall-Héroult cell consists of a steel shell lined with carbon (cathode) and carbon anodes suspended above the cell.

Alumina and cryolite (Na_3AlF_6) form a eutectic composition with reduced melting point (from $\sim 2000^\circ\text{C}$ to $\sim 960^\circ\text{C}$) and improve electrical conductivity.

Reactions

- Electrolysis: $\text{Al}_2\text{O}_3 = 2 \text{Al}^{3+} + 3 \text{O}^{2-}$
 $\text{Al}^{3+} + 3 \text{e}^- = \text{Al}$
- Reaction with anode $\text{C} + 2 \text{O}^{2-} = \text{CO}_2 + 4 \text{e}^-$
- Overall reaction: $2 \text{Al}_2\text{O}_3 + 3 \text{C} = 4 \text{Al} + 3 \text{CO}_2$
(1.5 ton CO_2 per ton Al – carbon reduces voltage)

- What are the limitations of primary aluminum production via this process? (1P)
High energy consumption; significant CO_2 emissions from carbon anodes.

- b) The recycling of aluminum alloys plays a key role in reducing the carbon footprint of the aluminum industry.

- Explain why recycling of aluminum is critical for sustainability (1P)
Reduces energy use (95% less than primary production), lowers CO_2 emissions, conserves resources.

- Explain why separating different series of aluminum alloys (e.g., 2xxx, 5xxx, and 6xxx) during the recycling process is essential for maintaining mechanical properties. (2P)
Maintains mechanical properties by avoiding contamination of alloys with differing compositions.

c) An Al alloy of the type AA6061 is widely used in automotive structures due to its excellent mechanical properties and corrosion resistance.

- What are the main alloying elements of the alloy and what are their role? (2P)

Mg: Strengthens via solid solution.

Si: Forms Mg₂Si precipitates for precipitation strengthening.

- What does the "T6" designation indicate in AA6061-T6? (1P)

Solution heat-treated and artificially aged.

d) Impurities are critical for the performance of Al alloys

- How does the content of Fe as a main impurity element and remelting cycles affect the mechanical properties of AA6061 (e.g., strength, ductility, fatigue resistance)? (2P)

Fe forms brittle intermetallics, reducing ductility and fatigue resistance; remelting increases impurity accumulation.

- Propose strategies to mitigate the degradation of mechanical properties in recycled 6061 aluminum alloy. (2P)

Use of refining agents to reduce Fe content.

Alloying with e.g. Ti to modify Fe intermetallics.

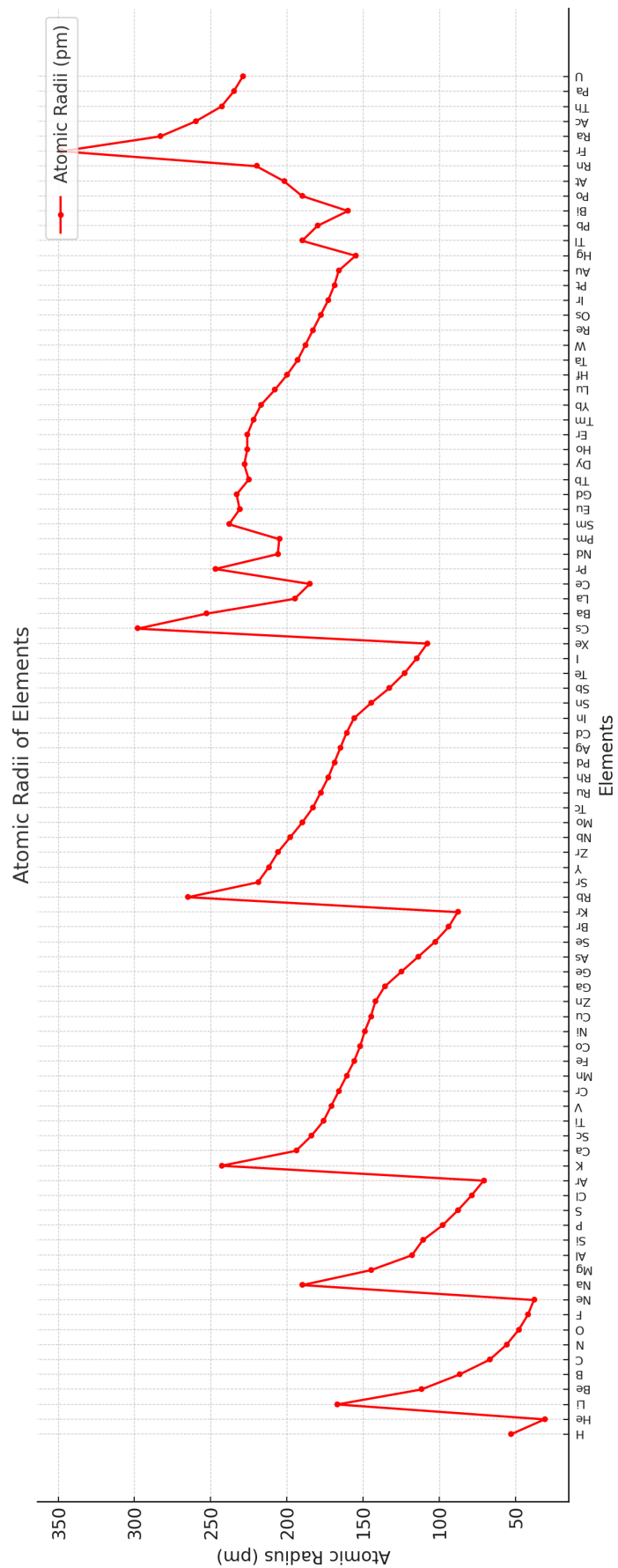


Figure 9. Atomic radii of elements