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 (16P)

a) Basic Knowledge (one or several answers are possible per question)

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

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

- 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

- 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

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

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

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

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

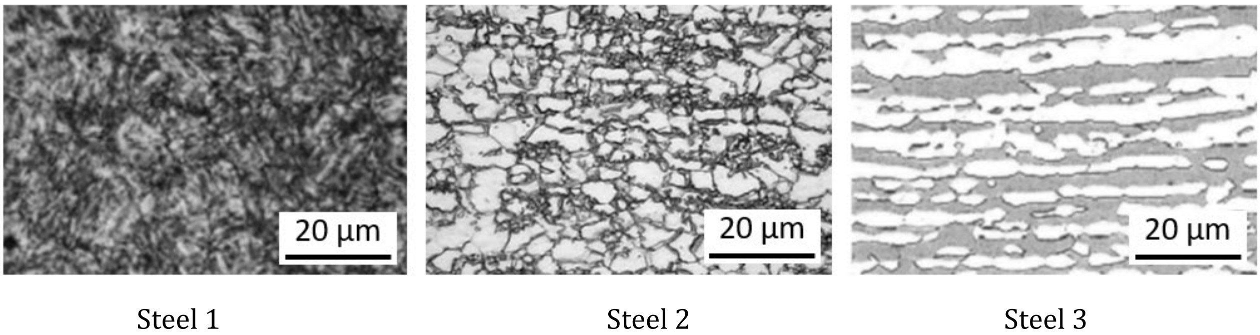

Figure 1. Microstructure of unknown steels

- 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).

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.

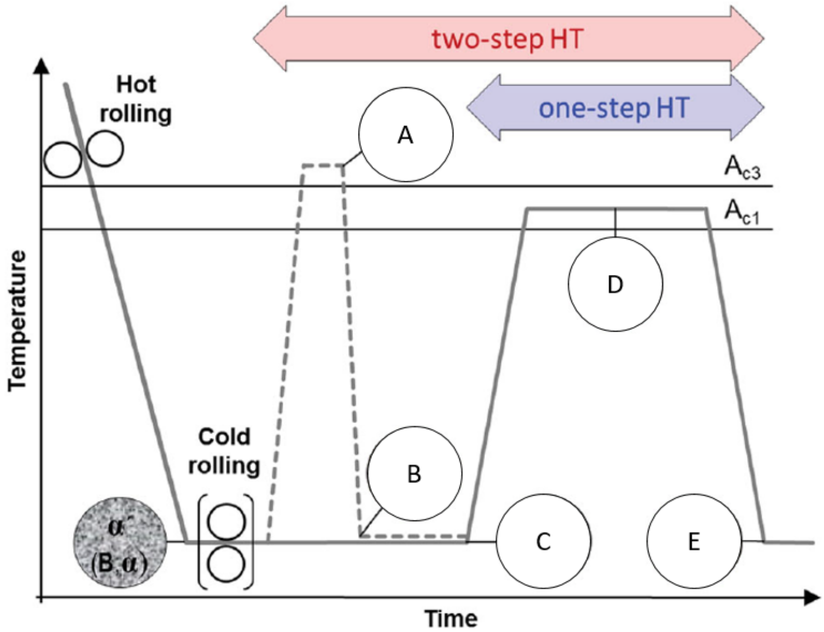

Figure 2. Illustrations of the one-step HT and the two-step HT routines.

- 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).

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

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

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

2) Nickel Alloys (15P)

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.

		Elements (wt.%)											
Alloy	**Generation**	**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.

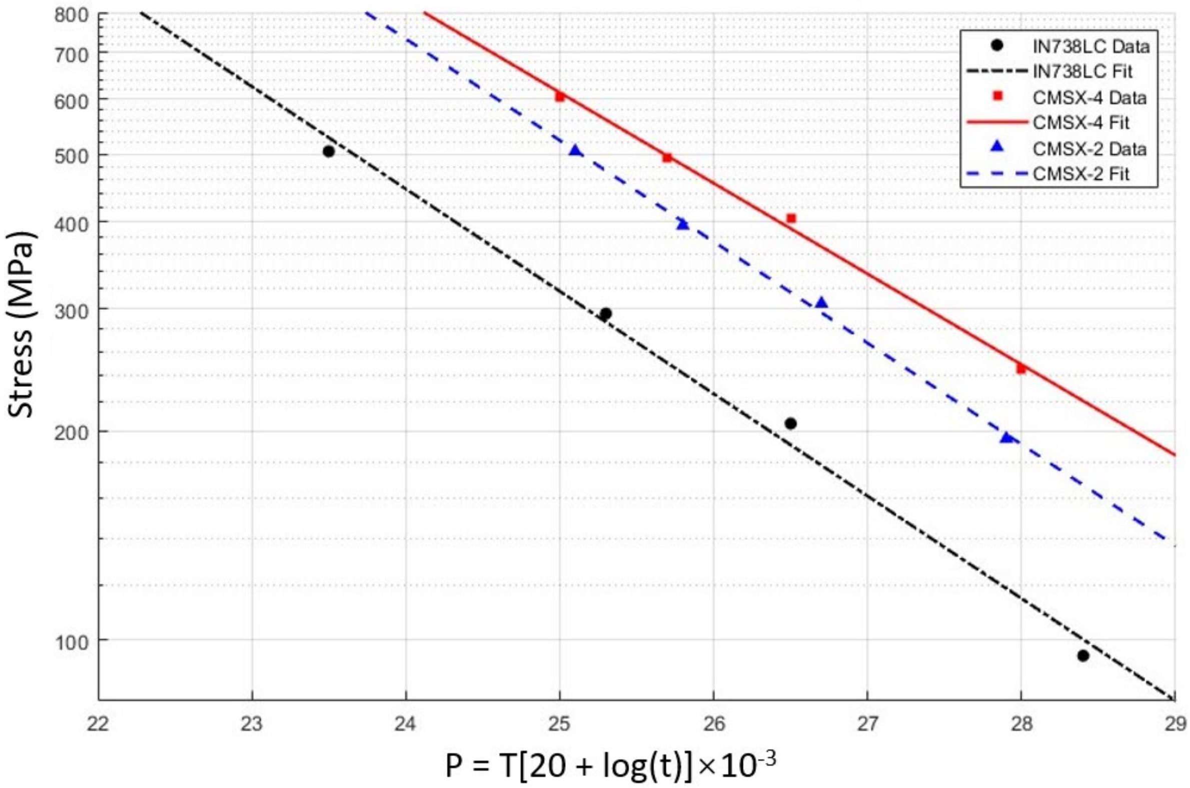

Figure 3. Larson-Miller diagrams of IN738-LC, CMSX-2 and CMSX-4

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)

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

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)

c) Why are Zr, B, and C included in IN-738LC but absent in CMSX-2 and CMSX-4? (1P)

d) Considering their chemical compositions, explain the increased creep performance of CMSX-4 in comparison with CMSX-2. (2P)

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

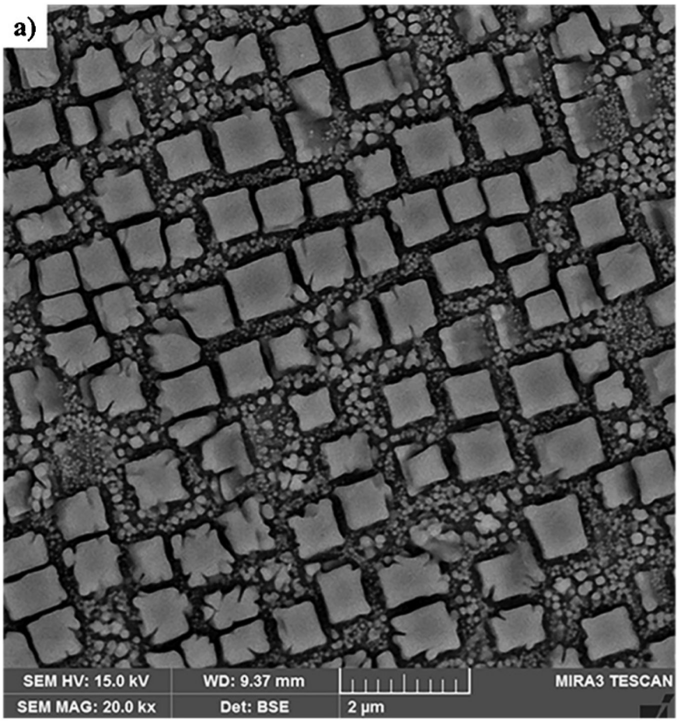

Figure 4. SEM – micrograph of IN-738LC after heat treatment

- 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)

- 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)

3) Titanium Alloys (14 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)

b) Explain the high corrosion resistance and biocompatibility of cp-Ti? (1P)

c) What are the main differences between the different grades of cp-Ti (grade1 – grade 4)? (2P)

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)

a) b)

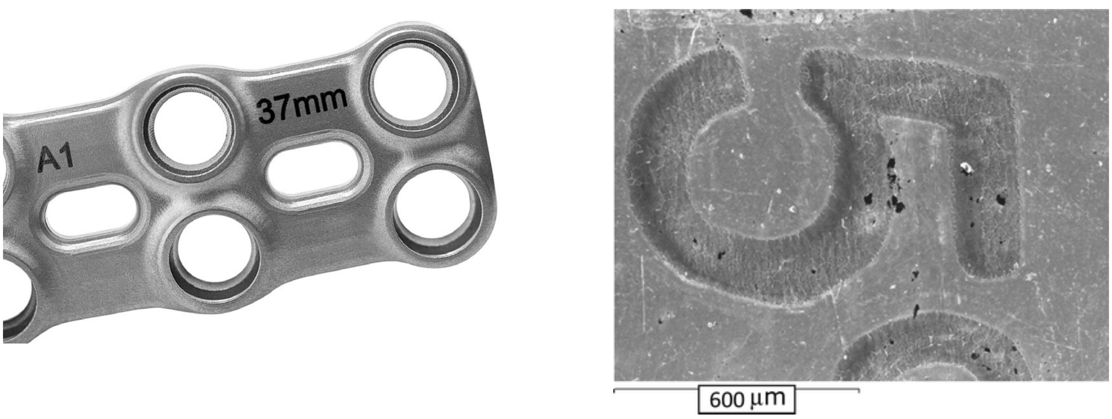

Figure 5. Laser-marked cp-Ti implant; a) bone plate; b) SEM of marked region

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 (± 1200) for unmarked samples and 24'447 (± 1348) for marked samples.

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

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)

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

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

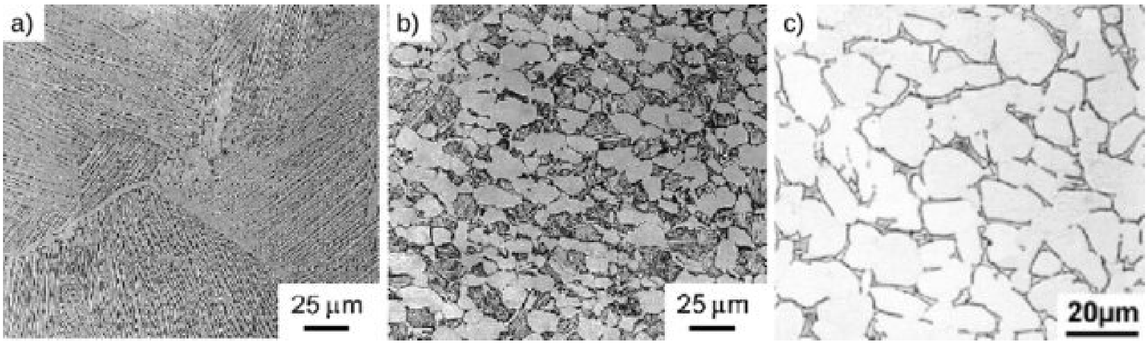

Figure 6. Optical micrograph- microstructures of Ti6Al7Nb after different thermos-mechanical treatments

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

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.

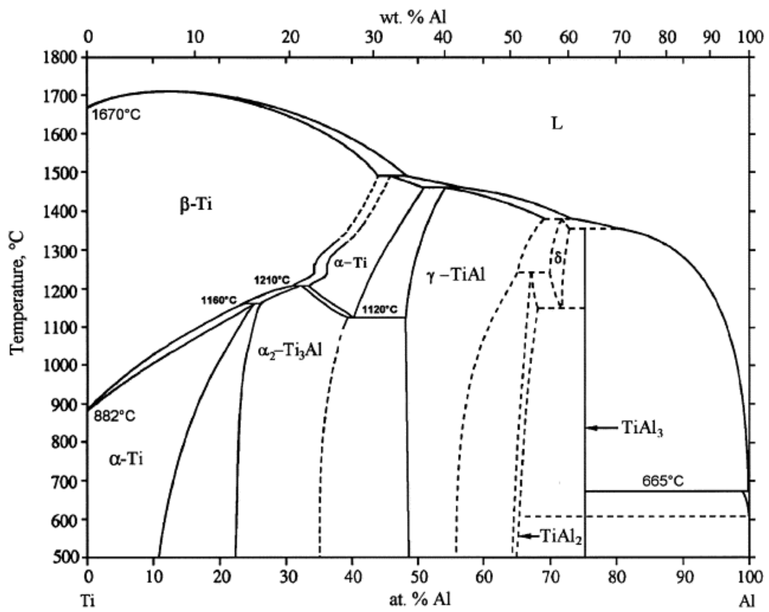

Figure 7. Binary Ti-Al phase diagram

- Indicate the compositional range of technical Ti aluminides. Which phases are formed? (2P)

- Why are Ti aluminides preferred alloys for high-temperature aerospace applications? (2P)

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

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	
Hf20Mo15Nb25Ta25Ti25	
Zr58Cu16Ni13Al10Nb3	

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

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

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)

- 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)

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

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 2.5×10^{-6} m^2/s. Calculate the maximum critical cooling rate required for this alloy to be defined as bulk metallic glass (1.5P).

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)

- What are the limitations of primary aluminum production via this process? (1P)

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)

- 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)

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)

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

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)

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

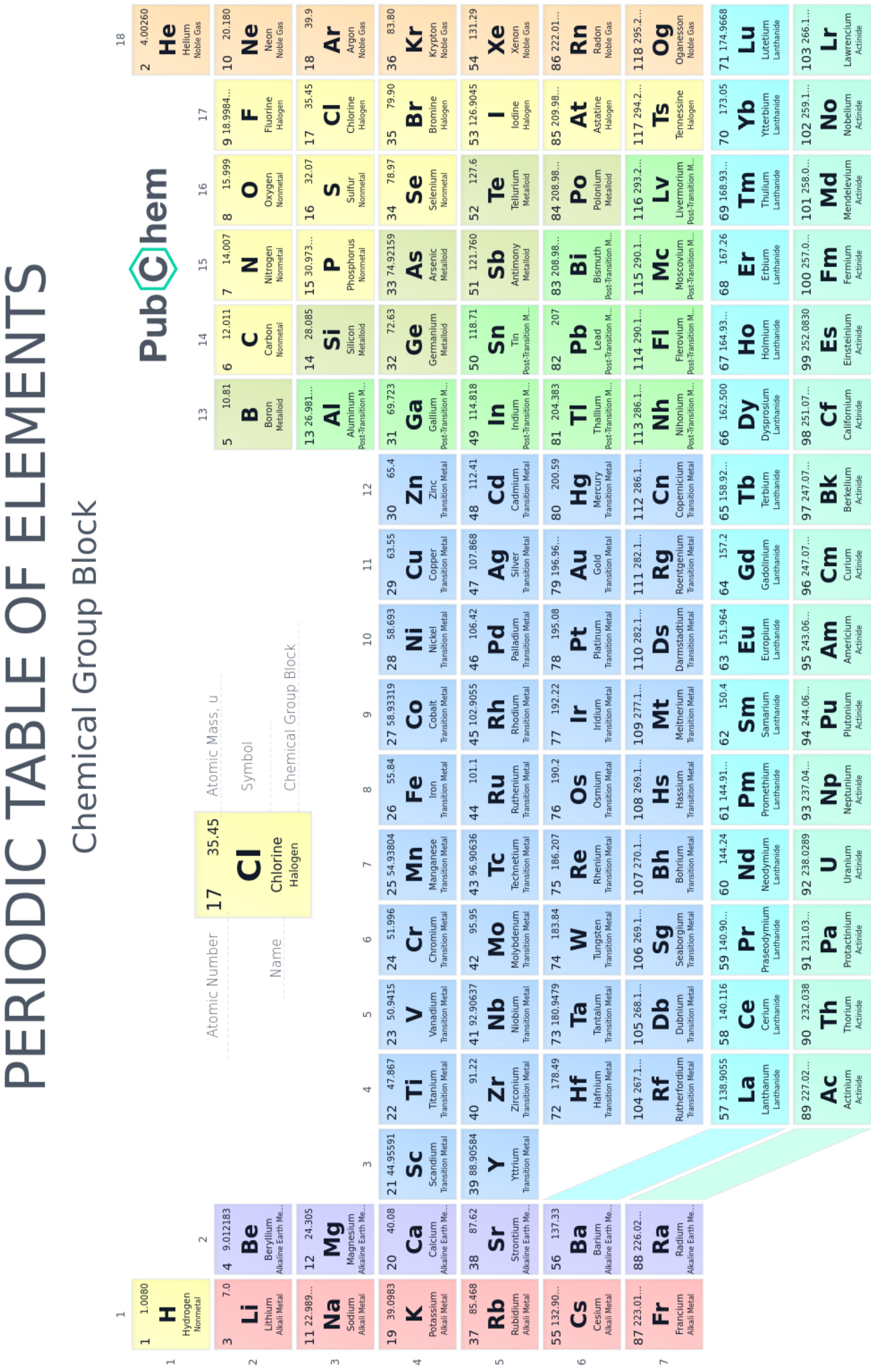

Figure 8. Periodic Table of Elements

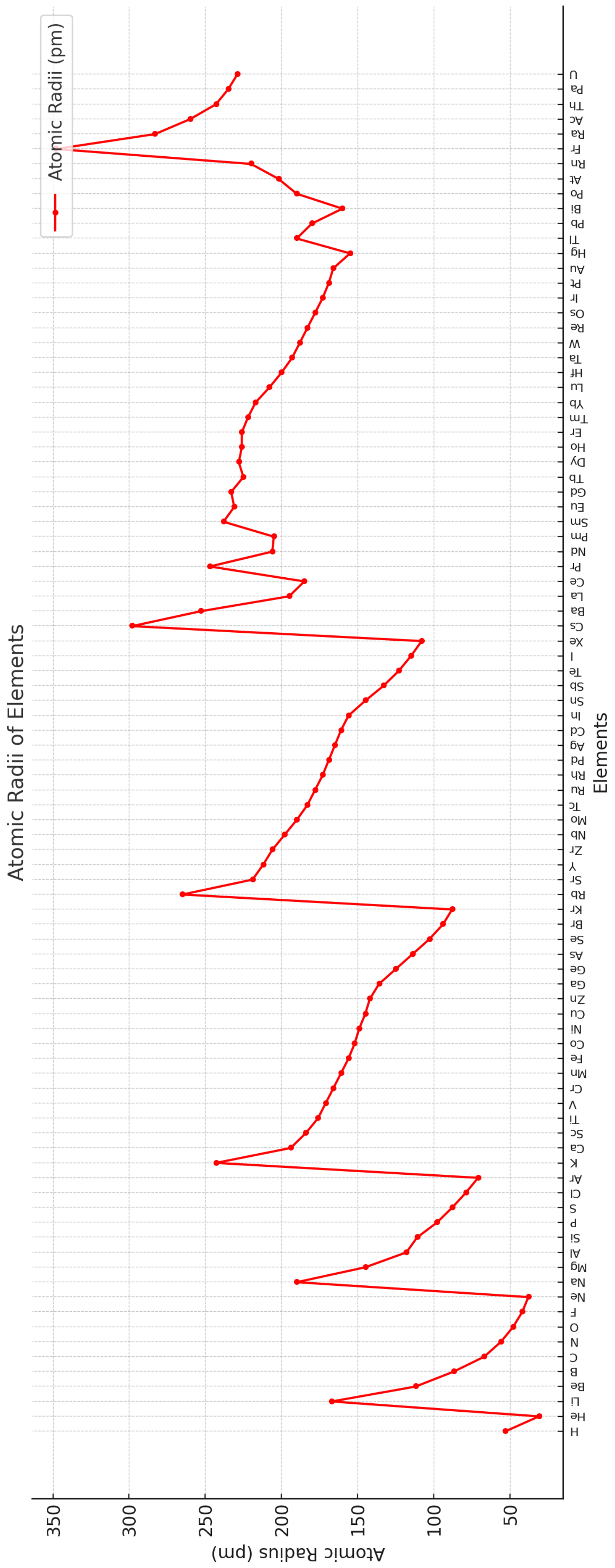

Figure 9. Atomic radii of elements