



FACULTY OF ENGINEERING AND THE ENVIRONMENT
DEPARTMENT OF METALLURGICAL ENGINEERING
PHYSICAL METALLURGY
EMG 3104
Final Examination Paper
September 2024

This paper consists of 6 pages

Time Allowed: 3 hours
Total Marks: 100
Examiner: Mr P Chamboko

INSTRUCTIONS

1. The examination paper consists of FIVE questions, **Answer ANY FOUR QUESTIONS**
2. Where a question contains subdivisions, the mark value of each subdivision is shown in brackets.
3. Illustrate your answer, where appropriate, with clearly labeled diagrams.
4. Start each question on a new page.
5. Use of calculators is permissible

Additional requirements: Graph Paper

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NB: DO NOT TURN OVER THE QUESTION PAPER OR COMMENCE WRITING UNTIL INSTRUCTED TO DO SO

Question 1: {25 Marks}

- (a) A hot-rolled AISI 1040 steel bar (medium carbon steel) needs to be used for a high-strength shaft application. However, the hot-rolled condition produces a relatively coarse microstructure with lower strength.
- (i) Explain the concept of work hardening and how it influences the strength of metals. Briefly describe the limitations of work hardening for this application. **[5 marks]**
 - (ii) A suitable heat treatment process (or combination of methods) is recommended to improve the strength of the AISI 1040 steel bar. Explain the microstructural changes during this heat treatment and how they contribute to the increase in strength. Consider factors like grain size and precipitation hardening mechanisms (if applicable). **[5 marks]**
- (b) Based on melting temperature, oxidation resistance, yield strength, and degree of brittleness, discuss whether it would be advisable to hot work or cold work (a) aluminum alloys, and (b) magnesium alloys. **[5 marks]**
- (c) The figure 1 below is the hafnium–vanadium phase diagram, for which only single-phase regions are labeled. Specify temperature–composition points at which all eutectics, eutectoids, peritectic, and congruent phase transformations occur. Also, for each, write the reaction upon cooling. **[10 marks]**

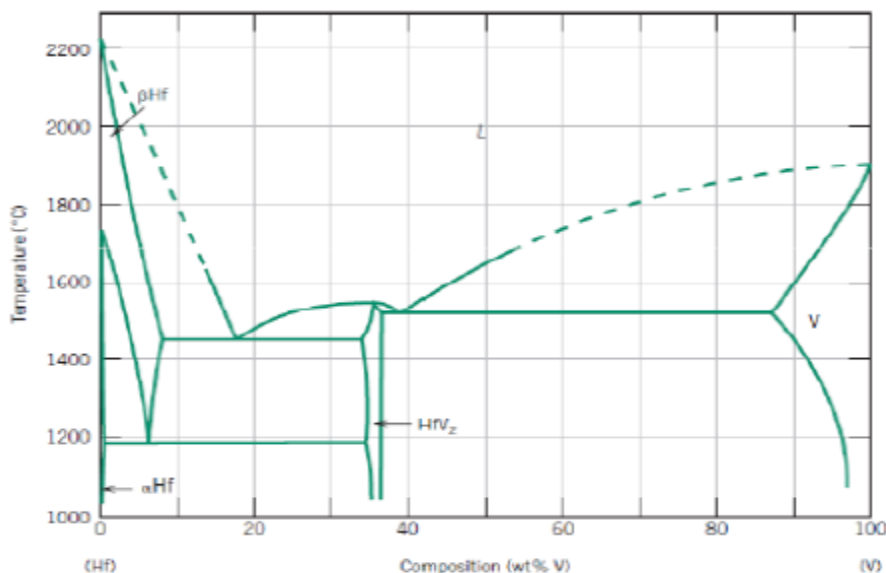


Figure 1: hafnium–vanadium phase diagram

Question 2: {25 Marks}

(a) A critical component in a pressure vessel application is manufactured from a high-strength aluminum alloy. During a routine inspection, a crack is discovered on the component's surface.

(i) Discuss two possible mechanisms that could have led to crack formation in the aluminum alloy component. Briefly explain the factors that might contribute to each mechanism. [6 marks]

(ii) Describe two non-destructive testing (NDT) techniques that could be used to evaluate the extent and severity of the crack in the aluminum component. Explain the principle behind each NDT technique and its suitability for this application. [8 marks]

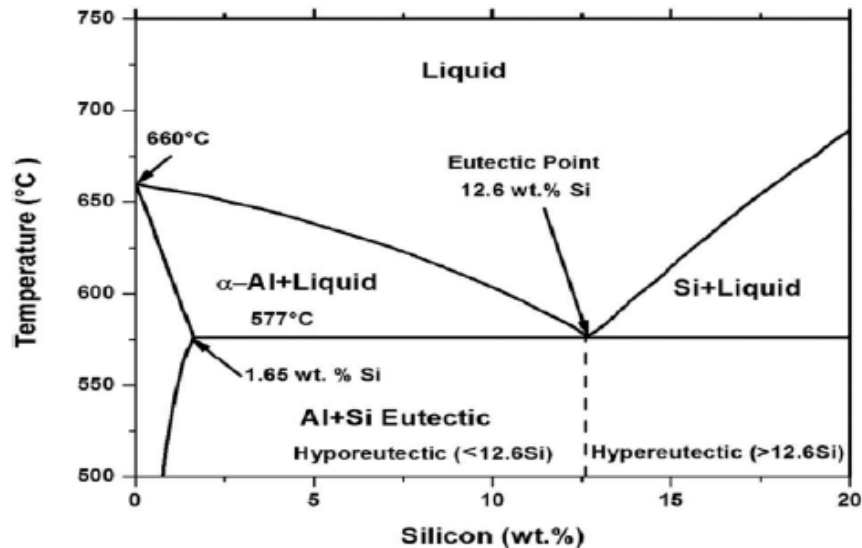


Figure 2: Al-Si phase diagram.

(b) A eutectic aluminum-silicon alloy (Al-Si) is rapidly cooled (quenched) from its liquid state. Using a sketch of the Al-Si phase diagram in Figure 2, explain how the microstructure will differ from the equilibrium microstructure obtained during slow cooling. Discuss the potential consequences of rapid cooling on the mechanical properties of the Al-Si alloy. [6 marks]

(c) A piece of steel which was quenched after prolonged holding at 700°C was found to have a ferrite martensite structure.

- (i) Analyze the conditions that led to the formation of this microstructure. Discuss the implications of prolonged holding at 700°C on the phase transformation behavior of steel, particularly about the kinetics of austenite formation, the subsequent quenching process, and the potential effects on mechanical properties. Additionally, consider how variations in composition or the presence of alloying elements might further influence the resulting microstructure. **[5 marks]**

Question 3: {25 Marks}

- (a) A stainless steel plant produces the following stainless steel grades in a 45mm plate form: S44635, S34700, S32750, S30100, and S34565. The composition of these commercial grades is provided in Table 1:

Table 1: Composition of steels (wt %)

UNS number	C	Cr	Ni	Mn	Si	Ti	Mo	N	Fe	Other Element(s)
S44635	0.035	35	3	—	—	0.5	5	0.035	Bal	—
S34700	0.090	19	12	3	1	—	—	—	Bal	0.8Nb
S32750	0.040	35	8	1.3	1	—	5	0.4	Bal	—
S30100	0.100	17	8	3	1	—	—	—	Bal	—
S30700	0.030	27	17	5.7	1	—	7	0.4	Bal	0.1Nb

- (i) Using the Schaeffler diagram provided (figure Q3), define the likely phase constitution(s) obtained in the stainless steel grades upon solidification under equilibrium conditions. The nickel equivalent ($Nieq$) and chromium equivalent ($Creq$) can be calculated by using the expressions provided below:

$$Nieq = \%Ni + \%Co + 30(\%C) + 25(\%N) + 0.5(\%Mn) + 0.3(\%Cu),$$

$$Creq = \%Cr + 2(\%Si) + 1.5(\%Mo) + 5(\%V) + 5.5(\%Al) + 1.75(\%Nb) + 1.5(\%Ti)$$

[18 marks]

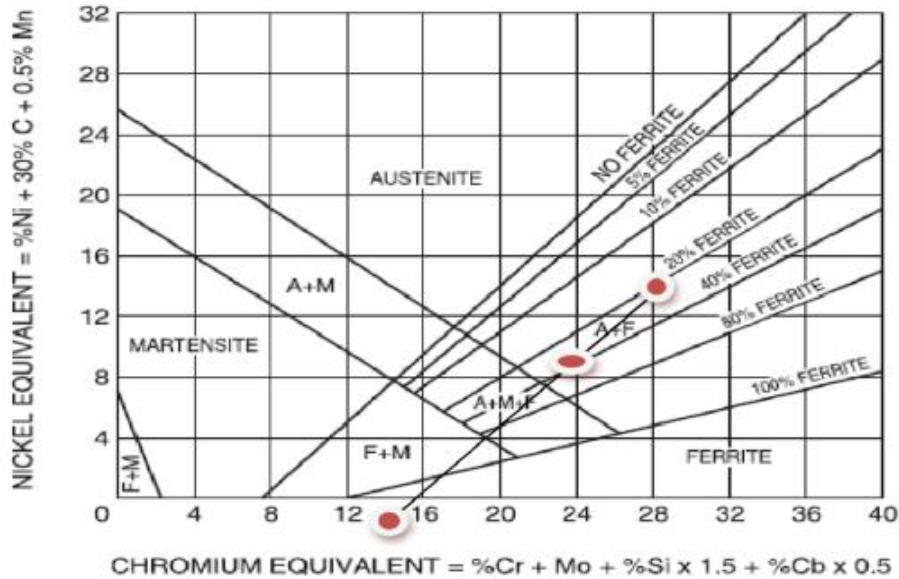


Fig Q3 Schaeffler diagram

- (ii) Explain which of the above-mentioned stainless steel grades may be more prone to a subsequent phase transformation, if subjected to a 40% cold rolling reduction performed at 253K. [7 marks]

Question 4: {25 Marks}

- (a) Diffusion welding is a solid-state joining process used for dissimilar metals. Imagine you need to join a copper (Cu) sheet to a nickel (Ni) sheet using diffusion welding.
- (ii) Explain the key principles of diffusion welding. Describe the factors that influence the success of a diffusion welding process. [5 marks].
- (iii) Discuss any potential challenges that might be encountered during diffusion welding of Cu and Ni. Suggest strategies to overcome these challenges and ensure a successful weld joint. [5 marks]
- (b) A sheet of BCC iron 2 mm thick was exposed to a carburizing gas atmosphere on one side and a decarburizing atmosphere on the other side at 675°C. After having reached a steady state, the iron was quickly cooled to room temperature. The carbon concentrations at the two surfaces of the sheet were determined to be 0.015 and 0.0068 wt%. Compute the diffusion coefficient if the diffusion flux is 7.36×10^{-9} kg/m²-s (Hint: convert the

concentrations from weight percent to kilograms of carbon per cubic meter of iron. [10 marks]

- (c) A bullet hole is made in a plate of aluminum, and the plate undergoes an annealing process following the impact.
- (i) Describe how the grain size will vary from the hole outward after the annealing process. Consider the effects of mechanical deformation on the microstructure and how annealing influences grain growth and recrystallization. **[5 marks]**.

Question 5: {25 Marks}

- (a) You have been given a gear with a broken tooth that has failed prematurely in service. The normal heat treatment is carburizing, hardening, and tempering. Describe completely how this gear would be studied to determine possible metallurgical causes for failure. **[5 marks]**.
- (b) A 0.2wt% C plain carbon steel is slowly cooled from 750°C to a temperature just slightly below 723°C. Assuming that austenite is completely transformed:
- (i) Calculate the weight percent of the micro-constituents and of the phases formed. **[8 marks]**
- (ii) Describe in detail the phase transformations that would have taken place during this slow cooling sequence. **[6 marks]**
- (iii) With the aid of a schematic diagram, describe the mechanism of formation of upper and lower bainite, concerning the isothermal transformation of a eutectoid (0.76% wt C) plain carbon steel. **[6 marks]**

END OF EXAMINATION