**Department of Mechanical Engineering**
**University of Saskatchewan**

# ME324.3 Engineering Materials

FINAL EXAMINATION (CLOSED BOOK)

**STUDENT NAME:** ______________________________

| | | | |
|---|---|---|---|
| **Instructor:** | I. N. A. Oguocha | **Date:** Saturday, 15th December 2007 | |
| **Time Allowed:** | 3 h | **Place:** 2C01 & 2C02 (Engineering) | |

**READING TIME:** 10 MINUTES **TOTAL POINTS: 893**

**INSTRUCTIONS**
1. ANSWER ALL QUESTIONS
2. FOUR formula/help sheets are allowed but must be turned in with your answer script(s), worksheet and question paper. Calculators are allowed.

**WARNING:** This is a very busy exam. Do not waste your time on irrelevancies and verbose statements. Wherever applicable, go straight to the point (s).

**QUESTION 1** (95 Points)

(a) State the respective temperatures at which the solubility of carbon is maximum in (i) *austenite* and (ii) *ferrite*. (6 Points)

(b) How many times is the maximum solubility of carbon in austenite greater than in ferrite? (6 points)

(c) State the minimum *austenitizing temperature* for a plain-carbon steel containing (18 Points) (i) 0.3 wt%C, (ii) 0.77 wt.%C, and (iii) 0.9 wt.%C. Use Figure Q1.

(d) Why do proeutectoid phases in plain-carbon steels nucleate on grain boundaries? (8 Points)

(e) Explain with the help of labelled diagrams why Manganese (Mn) is intentionally added to plain carbon steels. (16 Points)

(f) A SAE 12150 *plain-carbon* steel is slowly cooled to 730 °C, then cooled to 700 °C and held there.
   (i) What would be the carbon content (*in wt.%*) of this steel? (5 Points)

   (ii) Of the cementite formed at 700 °C, what fraction of it formed at 730 °C? (20 Points)

   (iii) Sketch and clearly label the microstructure of the steel at (i) 730 °C and (ii) 700 °C (16 Points)

**QUESTION 2** (94 Points)

(a) Use labelled schematic diagrams only to distinguish between a TEM and a SEM (16 Points)

(b) The phenomenological equation for solid-state transformations exhibiting sigmoidal kinetic behaviour is given by the Avrami Equation

$$y = 1 - \exp\left(-kt^n\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad \text{Equation Q2}$$

(i) Using Equation Q2, show that $\ell n\left[\ell n\left(\frac{1}{1-y}\right)\right] = \ell n k + n \ell n t$ (18 Points)

(ii) What does the quantity (1 - $y$) represent? (4 points)

(c) AISI 1075 plain-carbon steel is fully austentized and quenched into room temperature water. What type(s) of martensite forms? (6 points)

(d) What is the effect of an increase in the wt% of alloys on the position of the nose of a TTT curve? What does the addition of Cobalt (Co) do to the nose of the TTT curve? (10 Points)

(e) In industrial practice, high-carbon steels which have been austenitized and quenched to room temperature are often chilled cryogenically. Why is this done? (8 Points)

(f) In TWO sentences only, distinguish between *bainite* and *martensite*. (8 Points)

(g) How does the *sensitization* of austenitic stainless steels differ from the ferritic grades? (12 Points)

(h) State THREE industrial processes that can cause sensitization in austenitic and ferritic stainless steels (12 Points)

**QUESTION 3** (100 Points)

An unalloyed steel tool used for machining aluminum and magnesium automobile wheels has been found to work well, but the purchase records have been lost and you do not know the steel's composition or AISI Number. An optical microscopy of a sample cut from this steel shows that its microstructure consists of 8% cementite and 92% martensite. You are tasked to order steel stock for this tool and develop a heat treatment procedure for reproducing this microstructure.

(a) Design a heat treatment that would reproduce the above microstructure if a further chemical analysis of the sample shows that the martensite contains 1.00wt.% C. (50 Points)

(b) Estimate the hardness of this steel. (15 Points)

(c) Estimate the tensile strength of this steel. (10 Points)

(d) Estimate the AISI Number of the steel so that you can order stock materials for the tool. (25 Points)

**QUESTION 4** (117 Points)

(a) You work for a local steel scrap recycling company. There is a great demand for stainless steel scrap and your company wants to cash in on this boom. However, from an internal market survey conducted by your company, it was found that the big stainless steel scrap users want it categorized from the source into *high-nickel stainless steels* and *low-nickel stainless steels* so as to enhance productivity and profitability. As a young engineer who has completed ME324 Class at the University of Saskatchewan, your immediate Engineering Manager assigns this project to you. You are required to design a simple and inexpensive method for recycling stainless steel scrap to meet your clients' requirements without performing any chemical analysis. Chemical analysis is very tedious and expensive. Justify your design. (25 Points)

(b) Type 304L stainless steel reactors containing ~0.02wt%C shows intergranular corrosion (IGC) after exposure to hot corrosive gases at 550°C for 14days.

(i) How can this be, since the alloy is normally resistant to IGC because of its low carbon content? Give details of how you arrived at your answer. (20 Points)

(ii) How could this attack be prevented, still using stainless steel? (16 Points)

Note: Figure Q4 shows temperature-time plots for various grades of Type 304 stainless steel.

(c) Your company manufactures stainless steel tanks for use in diverse applications including water and waste water treatment, brewing, potash mining, crude oil refining, industrial chemical processing, food processing, and military research. You recently fabricated and shipped new Type 347 stainless steel tanks that will be used to hold fuming nitric acid at temperatures ranging from 20 to 50 °C in a military research facility in a remote desert location. On a routine stock-taking exercise, it was discovered that some sheets used to fabricate the tanks were accidentally heated to slightly above 1320 °C and water cooled before tank fabrication by arc welding.

Knowing that fuming nitric acid will cause intergranular corrosion (IGC) and knifeline attack (KLA) on a sensitized austenitic stainless steel;

(i) Would you predict that either IGC or KLA could be a danger if these tanks are put into service as welded? Justify your answer. (18 Points)

(ii) If IGC or KLA is a danger, what are the possible practicable remedies? (18 Points)

(iii) How could the IGC or KLA problem have been prevented if it was found that the sheets underwent the stated heat treatment before welding? (20 Points)

**QUESTION 5** (142 Points)
Figure Q5 shows TTT diagrams for three plain carbon steels named Alloy I, Alloy II, and Alloy III. These steels belong to the *hypoeutectoid, eutectoid*, and *hypereutectoid* class but we do not know which belongs to which.

(a) Which diagram is associated with a composition that is *hypoeutectoid, eutectoid*, and *hypereutectoid*? (12 Points)

(b) Label the regions on each diagram as indicated by an arrow or a number. Use the following designations: (68 Points)
$A_s$ = Stable austenite, $A_u$ = Unstable austenite, *CP* = Coarse pearlite *FP* = Fine pearlite
*RA* = Retained austenite, *UB* = Upper bainite, *LB* = Lower bainite, *M* = Martensite, Nose
*P* = Pearlite, $P_s$ = Pearlite start, $P_f$ = Pearlite finish, $B_s$ = Bainite start, $B_f$ = Bainite finish
$Fe_3C$ = Cementite, $Fe_3C_s$ = Cementite start, *F* = Ferrite, $F_s$ = Ferrite start

(c) If a thin specimen of alloy II is quenched instantaneously from 900°C to 550°C, held for 1s, and quenched to room temperature, what microstructures will be present? What phases will be present in these microstructures? (15 Points)

(d) If a thin specimen of alloy III is quenched instantaneously from 800°C to 350°C, held for 20 seconds, and quenched to room temperature, what microstructures will be present? What phases will be present in these microstructures? (15 Points)

(e) Estimate the carbon content for the *hypoeutectoid* and *hypereutectoid* steels. Explain your reasoning (i.e., how you arrived at your answers). (28 Points)

**QUESTION 6** (135 Points)
An axle is to be manufactured for an industrial machine using a SAE 15XX plain-carbon steel. The design requirements call for a mixed microstructure and tensile strength of 1449 MPa. A check in your Spare Parts store shows you have two SAE 15XX steels, namely: SAE 1541 and SAE 15B41. You have only one heat treatment furnace. So, an *isothermal* heat treatment is not possible. The CCT diagrams for both steels are provided (see Figure Q6 in the Worksheet).

(a) Design a *non-isothermal* heat treatment that would enable you to obtain the required strength and microstructure for: (i) AISI 1541 and (ii) AISI 15B41. (70 Points)

(b) What microstructures would develop in the two steels after the heat treatment in (a)? Explain the main cause of the observed difference(s) in microstructure between these steels. (40 Points)

(c) Based on your engineering judgement, which of the two steels would you use for the design of the axle. Provide sound scientific and engineering justification for your answer. (25 Points)

**QUESTION 7** (210 Points)

(a) **Materials for automotive headlight lens** (60 Points)

The lens of an automobile headlamp protects the bulb and reflector and focuses the light where it is most needed. The project is to select materials for the lens.

***Material choice***. The requirements are:

- * Must be *transparent* with *optical quality*.
- * Must have a <u>minimum</u> *moldability index* of 4
- * Must have *very good* resistance to *fresh* and *salt water*
- * Must have *very good* resistance to *UV light*
- * *Good abrasion* resistance *(a* <u>minimum</u> of **18 Vickers Hardness** is required)
- * Must be disposed of by *recycling*
- * Must be *cheap* (<u>no more than</u> **CAN$5.0/kg**)

Use CES Edupack 2006 **Level 2** to select the best materials for this design.

(b) **Materials for the support of a cryogenic cooling system** (150 Points)

Materials are required for constructing a horizontal support rod for the container of a cryogenic cooling system that will be used in a future spacecraft (see Figure Q7). The conductive heat, *q*, into the container through the rod must be minimized to prevent malfunctioning of critical navigation instruments. The rod must be strong enough to support the mass of both the cooling liquid and the container. This is the *strength constraint*. Further, the support rod must not deflect excessively under load. This is the *deflection constraint*.

An optimization analysis of the support rod-liquid container system shows that the performance indices for selecting materials for the rod are

$$M_1 = \frac{\sigma_y^{\frac{2}{3}}}{\lambda} \text{ and } M_2 = \frac{E^{\frac{1}{2}}}{\lambda}$$

where $\sigma_y$ = yield strength, $E$ Young's modulus and $\lambda$ is the thermal conductivity of the material. $M_1$ is the performance index for satisfying the strength constraint while $M_2$ is that for satisfying the deflection constraint.

(i) Use CES EduPack (Level 2) to select FIVE materials that satisfy the requirements of performance index $M_1$. Show details of how you determined the slope of the selection line for $M_1$. Include printout(s) of your solution. (65 Points)

(ii) Use CES EduPack (Level 2) to select FIVE materials that satisfy the requirements of performance index $M_2$. Show details of how you determined the slope of the selection line for $M_2$. Include printout(s) of your solution. (65 Points)

(iii) Determine all the materials, if any, which satisfy the two selection criteria. If there is none, give reasons. (20 Points)

**Note: CES printouts must be included to get full marks in Question 7.**

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**ME324.3 Engineering Materials**

DEFERRED FINAL EXAMINATION (CLOSED BOOK)

$15^{th}$ December 2007

**WORKSHEET**

## Important parameters and relations

| **Microstructure** | **BHN** (3000kg load) |
|---|---|
| Ferrite (a) | 80 |
| Spheroidite ($P_s$) | 150 |
| Coarse Pearlite ($P_c$) | 240 |
| Medium Pearlite ($P_m$) | 280 |
| Fine Pearlite ($P_f$) | 380 |
| $Fe_3C$* | 800-1800 |

* Depends on crystallographic orientation.

$$\sigma_{tensile}(MPa) = 3.45 \times HB$$

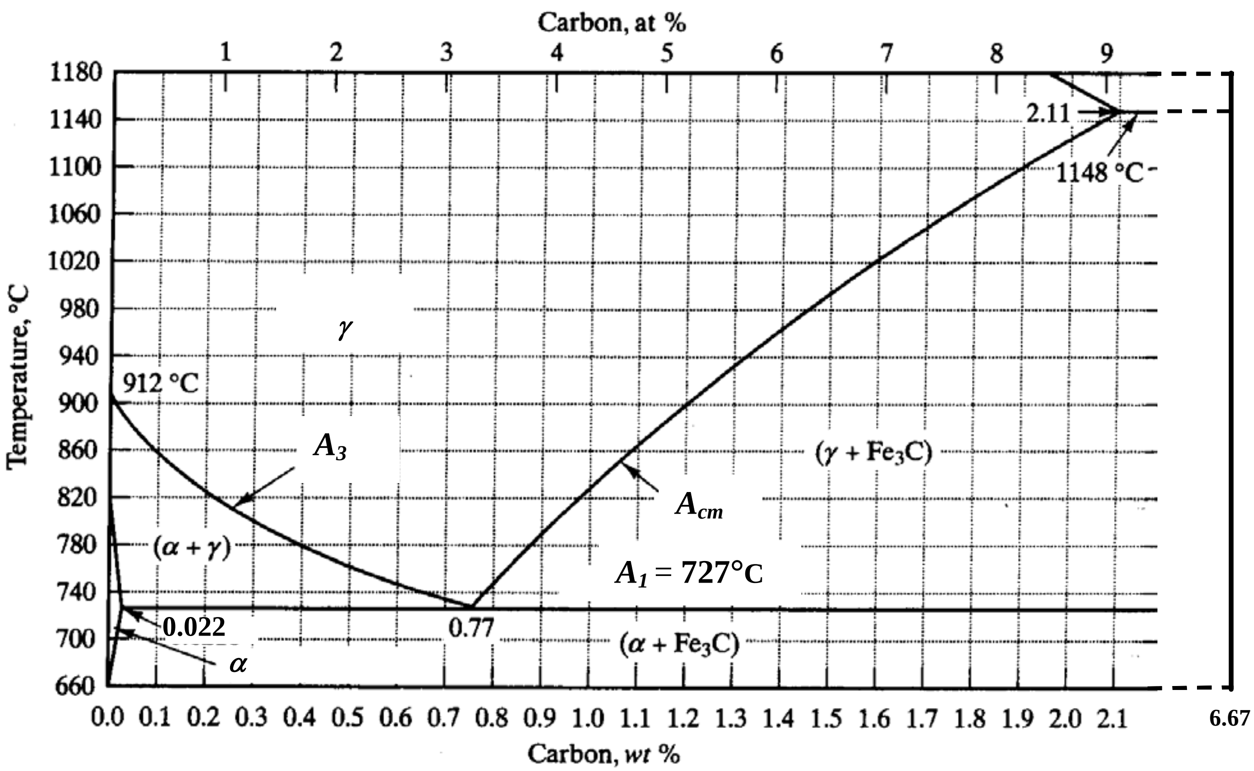
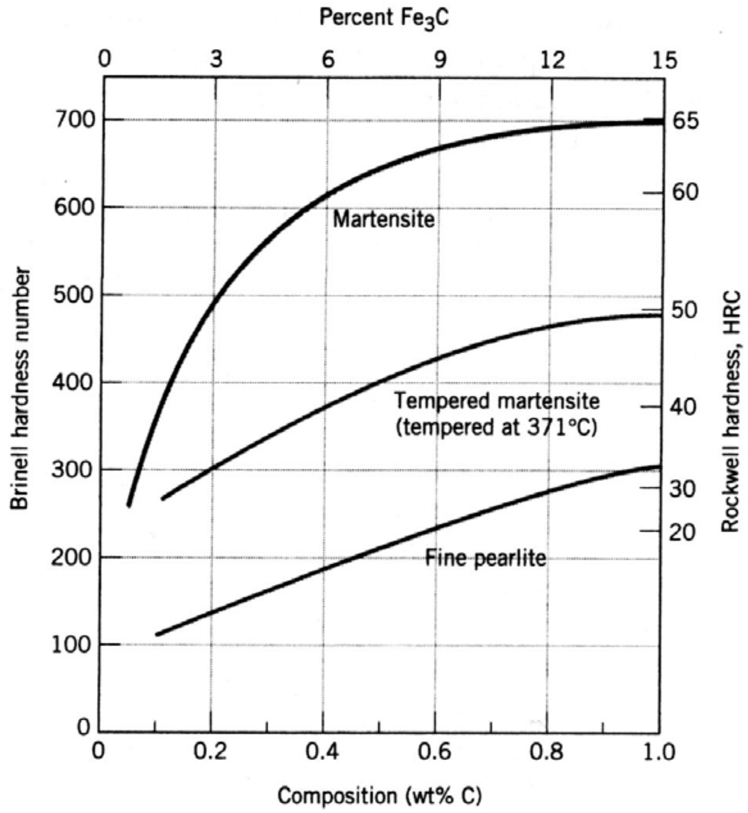



**Figure Q1**

**Student Name:________________________** **Student #:___________**




Hardness of martensite, tempered martensite and fine ferrite as a function of carbon content.

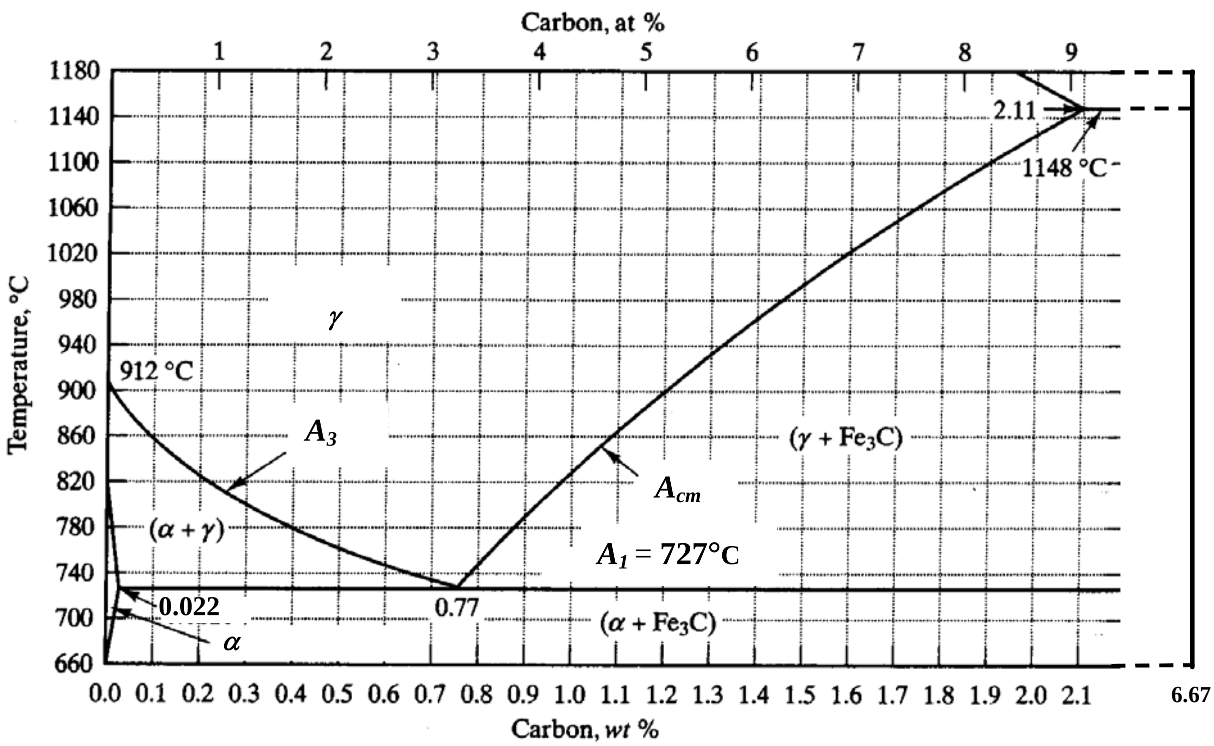



**Figure Q3**

**Student Name:________________________** **Student #:____________**

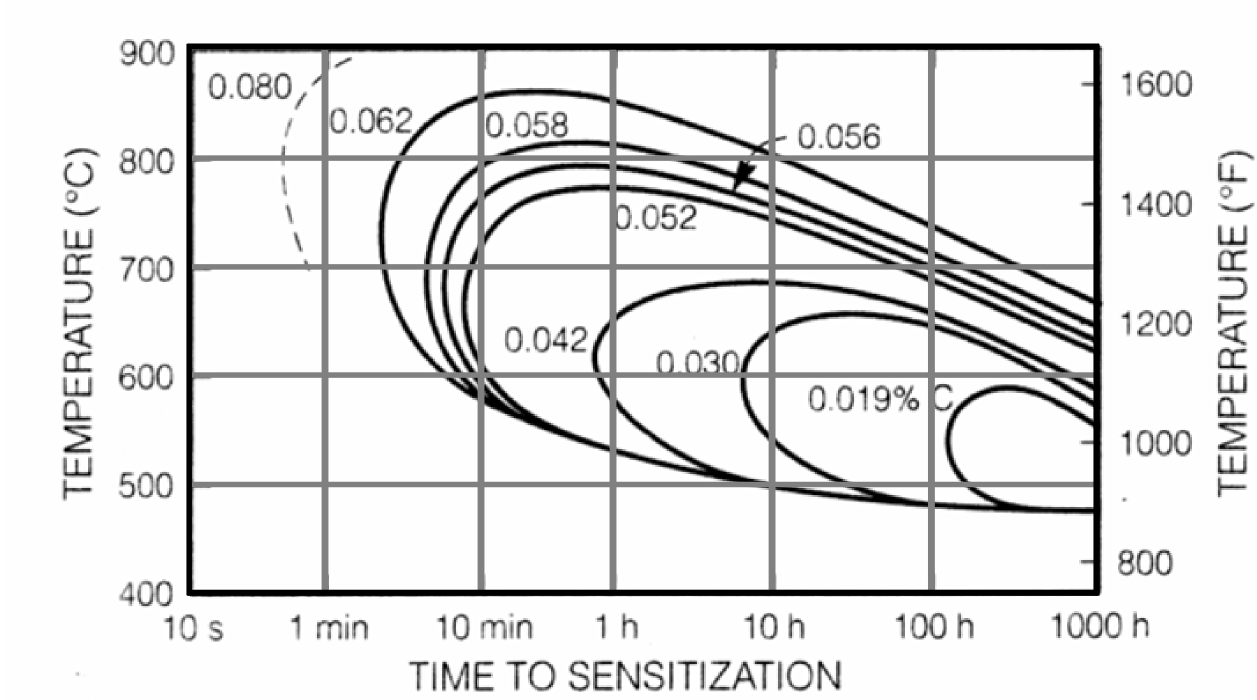



Figure Q4. Sensitization diagram for 18Cr-8Ni stainless steel of varying carbon content.

TableQ4. Temperature ranges for sensitization to IGC in austenitic stainless steels.

| Temperature | Metallurgical Reactions | REMRAKS<br>Unstabilized<br>Nb/Ta/Ti Absent<br>(E.g. Type 304) | REMRAKS<br>Stabilized<br>Nb/Ta/Ti Present<br>(Type 321 and347) |
|---|---|---|---|
| *Melting Point* | | | |
| **A** | All carbides dissolve | Rapid cooling prevents IGC | Rapid cooling and reheating to C causes KLA. Reheating to B prevents KLA |
| *1230℃* | | | |
| **B** | Nb/Ti carbide precipitates.<br>Cr carbide dissolves. | Rapid cooling prevents IGC | IGC prevented by precipitating dissolved carbide uniformly |
| *850℃* | | | |
| **C** | Cr carbide precipitates at grain boundaries | Sensitization to IGC caused | No sensitization. Nb/Ta/Ti carbides precipitated at B |
| *400℃* | | | |
| **D** | No reactions | Temperature too low | for adequate diffusion |

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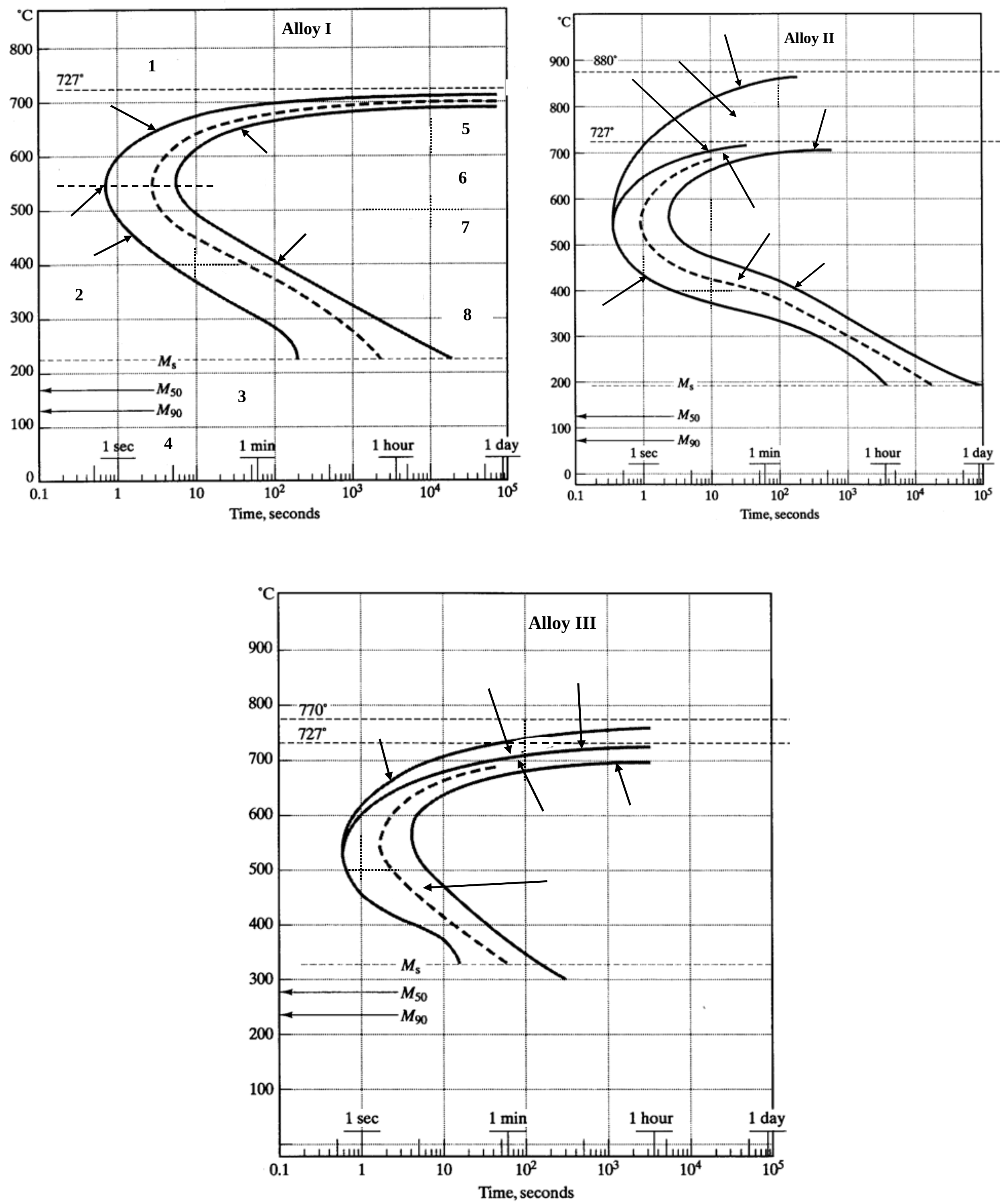
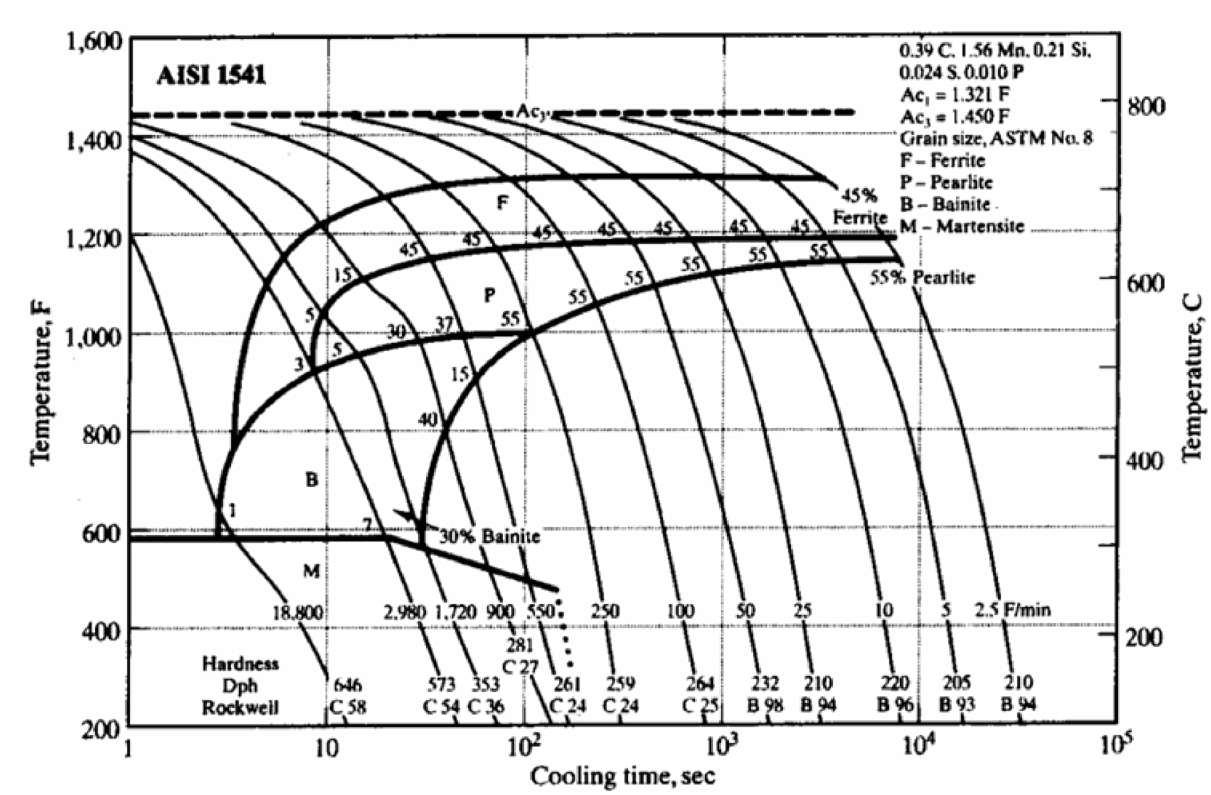



**Figure Q5**



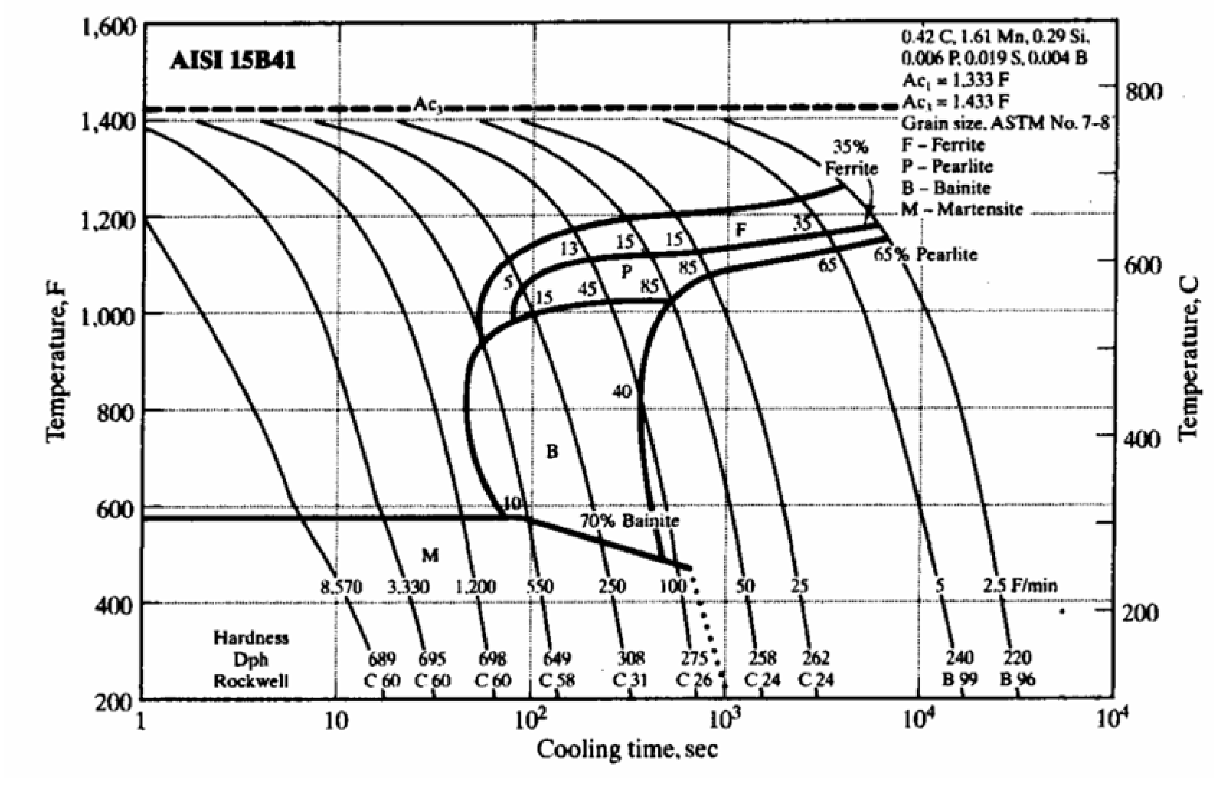




Figure Q6. CCT diagrams of AISI 1541 and 15B41 steels.

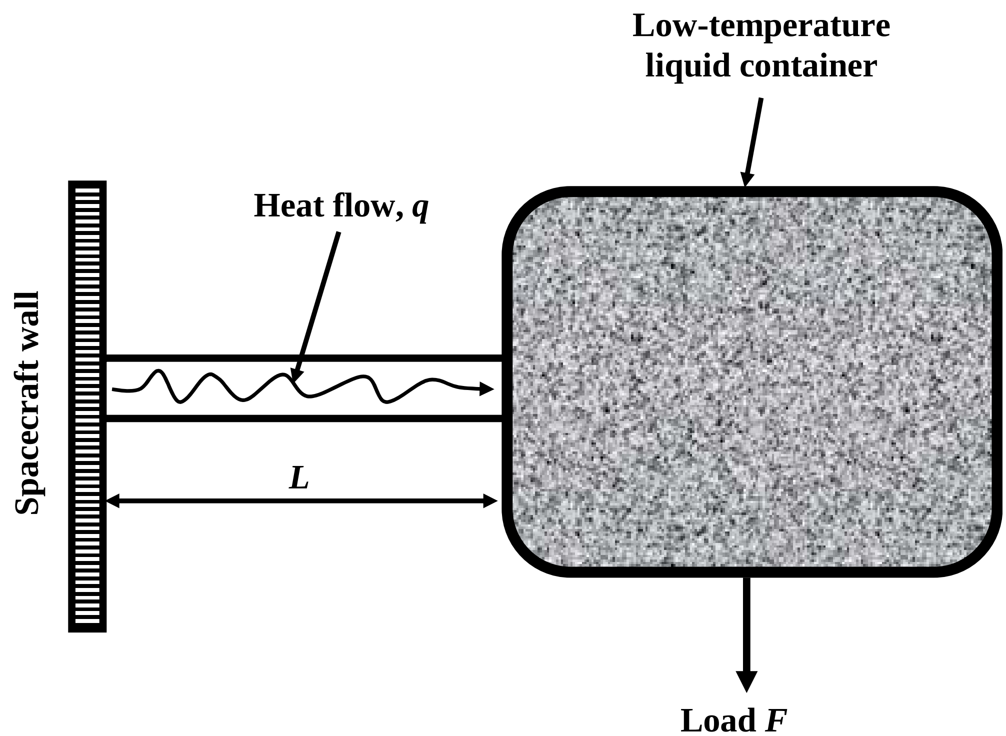

Low-temperature
liquid container
Heat flow, *q*
Spacecraft wall
*L*
Load *F*

**Figure Q7**