

# Montogue

## QUIZ MS101

### Heat Treatment and Metallurgy of Steel

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#### PROBLEMS

##### Problem 1

Match the phases of steel in Group I with the crystal structures in Group II.

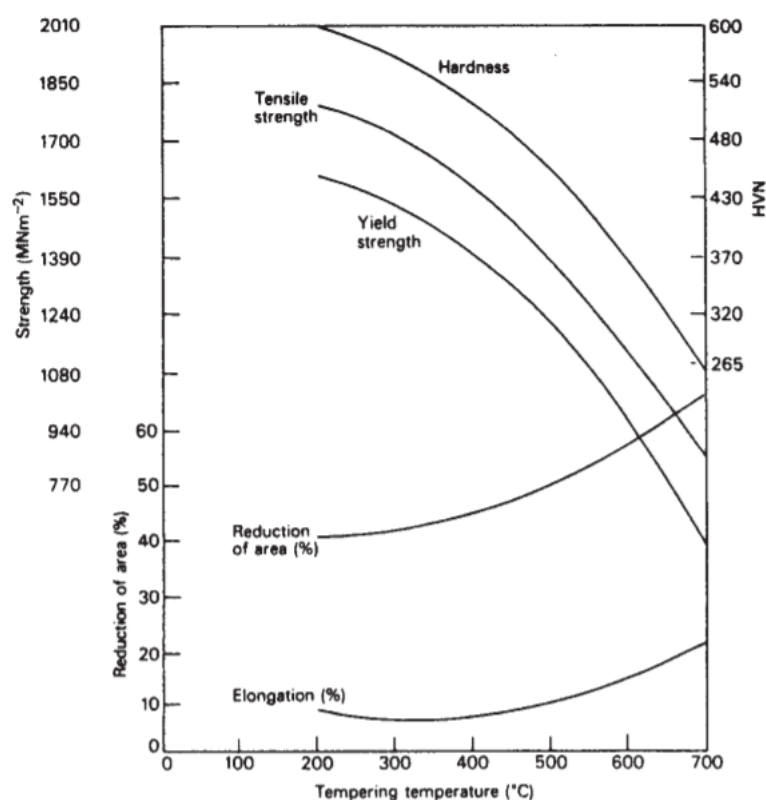
Group I	Group II
P. Martensite	1. Body-centered cubic (bcc)
Q. Cementite	2. Face-centered cubic (fcc)
R. Austenite	3. Body-centered tetragonal (bct)
S. Ferrite	4. Orthorhombic

- A) P-1, Q-4, R-3, S-1
- B) P-1, Q-3, R-2, S-4
- C) P-3, Q-4, R-2, S-1
- D) P-2, Q-1, R-3, S-4

##### Problem 2

Regarding aspects of the metallurgy of steel, true or false?

1. ( ) One of the most important variables that influence the hardenability of steel is grain size. In general, the hardenability of steels increases with increasing grain size.
2. ( ) The Jominy end-quench test is a standard procedure used to establish the hardenability of steels. It is applicable to most steels, including, say, highly alloyed air-hardened steels.
3. ( ) A wide range of mechanical properties is obtainable by tempering alloy steels between 200°C and 700°C, as illustrated by the graph below, which refers to a steel containing 1.5Ni-1Cr-0.25Mo-0.4C wt%. With reference to this chart, we can surmise that high tensile strength levels ( $\approx 1500 \text{ MNm}^{-2}$ ) can be attained by tempering at low temperatures, preferably no greater than 300°C. This is especially true for alloy steels.



**4.( )** Temper embrittlement occurs when steels are heated to a temperature range between 375°C and 575°C. It is attributed, among other factors, to the segregation of impurities such as antimony and phosphorus to the grain boundaries, since the ductile-to-brittle transition is directly dependent on the grain-boundary concentration of impurities. Once the aforementioned temperature range is achieved and maintained for the appropriate time, the microstructure of steel becomes irreversibly embrittled, even if remedial techniques such as additional heating are employed. As a result, the part must be scrapped.

**5.( )** Fuel-fired furnaces are some of the simplest settings for heat treatment of steel. It does pose some inherent drawbacks, however, such as the potential explosion hazard and need for extensive ventilation.

**6.( )** It has long been observed that small additions of certain elements, e.g. titanium, vanadium, and boron, can considerably improve the hardening properties of steel. The most effective element in this respect is boron. Hardenability of low-alloy steels increases substantially upon introduction of boron in amounts of thousandths of a percent. A further increase in the boron content improves the hardenability even further. The effect of boron on hardenability increases with greater carbon content.

**7.( )** Hardness decreases noticeably when alloy steels and addition-free steels are subjected to tempering between 500°C and 600°C. This decrease is attributed to the precipitation of martensite and coagulation of cementite. When the temperature is higher, the hardness of steels with additions of titanium, molybdenum, vanadium or tungsten decreases further, characterizing a phenomenon known as secondary softening.

**8.( )** All standard, low-carbon, medium-carbon, and high-carbon wrought steels can be normalized. Some variables are critical for the process to generate the refined grain structure characteristic of this process. For one, time at temperature is critical to ensure a homogeneous process, especially for thin, geometrically simple parts. Rate of cooling, in turn, is significantly influenced by the amount of pearlite, its size, and spacing of pearlite lamellae. At higher cooling rates, more pearlite forms and lamellae are finer and more closely spaced. Both the increase in pearlite and its greater fineness result in lower strength and hardness. As a rule, higher cooling rates mean softer parts.

**9.( )** Hardening of steel yields a martensitic structure whose maximum hardness depends on the dissolved carbon content in accordance with the formula  $H_{100\% \text{ Mart.}} = 60\sqrt{[C]} + 20$ , where  $[C]$  is the carbon content in wt%.  $H_{100\% \text{ Mart.}}$  is given in HRC. To check the quality of hardening achieved, the concept of degree of hardening,  $S$ , has been introduced; it is given by the ratio of the measured hardness to the maximum hardness as obtained from the foregoing formula. For highly stressed parts, the required  $S$  is often greater than 0.95, whereas a lower threshold of about  $S > 0.7$  is considered acceptable for less stressed parts. Consider a steel with 0.55 wt% carbon content and measured hardness of 40 HRC. We conclude that this steel does not satisfy the threshold for less stressed parts, i.e., its degree of hardening is less than 0.7.

**10.( )** Situations in which heat treatment of steel by flame hardening may prove especially useful include the processing of parts in which only a small segment, section, or area requires modification, or when the dimensional accuracy of a part is impracticable or difficult to attain by ordinary furnace heating and quenching.

**11.( )** Surface carburizing methods used in steel include gas carburizing and vacuum carburizing. One of the advantages of vacuum carburizing is the higher rate of flow of carburizing gas into the furnace, which is made possible by the inherently high pressure at which the process is conducted. In addition, the formation of free carbon (sooting) is less of a problem for this method, especially if the diffusing gas is acetylene or propane.

**12.( )** In carbonitriding of steel, ammonia is introduced into the carburizing atmosphere.  $\text{NH}_3$  decomposes at carburizing temperature and releases nitrogen with the ability to be absorbed by the steels. It differs from carburizing and nitriding because, in carburization, the gases normally do not contain nitrogen and, in nitriding, the gases contain nitrogen primarily; in carbonitriding, the cases contain both carbon and nitrogen. Nitrogen has some advantageous peculiarities in its interaction with the steel microstructure. For one, it stabilizes austenite, thus reducing the diffusion-controlled transformation of austenite to ferrite and pearlite and lowering the martensite start temperature ( $M_s$ ). The stabilized austenite leads to better hardenability. Nitrogen also stabilizes martensite – indeed, C-N

martensite has a better tempering behavior than ordinary martensite. Carbonitriding is performed at higher temperatures than typical carburization so as to ensure that the nitrogen potential is as high as possible.

**13.( )** In austempering, the steel part is quenched in a salt bath and held at a temperature greater than the  $M_s$  temperature for longer than in martempering. This is done to inhibit the formation of bainite that is characteristic of the latter process.

**14.( )** The temperature of cold treatment most often used in steels is  $-84^\circ\text{C}$  ( $-120^\circ\text{F}$ ). Much like in heat treatment, achievement of temperatures below this fixed value by, say, 5 or 10 degrees may lead to unwanted microstructural transformations, especially if the exposure period is prolonged.

### Problem 3

Match the heat treatment processes in Group I with the resultant steel microstructure in Group II.

Group I	Group II
P. Martempering	1. Coarse pearlite
Q. Normalizing	2. Fine pearlite
R. Subcritical annealing for a long time	3. Tempered martensite
S. Full annealing	4. Spheroidized cementite in a matrix of ferrite

- A) P-1, Q-4, R-3, S-2
- B) P-2, Q-3, R-1, S-4
- C) P-4, Q-1, R-2, S-3
- D) P-3, Q-2, R-4, S-1

### Problem 4

Consider the gas carburization of type 1020 steel at  $930^\circ\text{C}$ . The steel has a nominal carbon content of 0.20% and the carbon content at the surface is 0.80%. The diffusion coefficient under these conditions is  $1.25 \times 10^{-11} \text{ m}^2/\text{s}$ . The time (min) necessary to increase the carbon content to 0.50% at 0.5 mm below the surface is most nearly:

- A)  $t = 251 \text{ min}$
- B)  $t = 362 \text{ min}$
- C)  $t = 480 \text{ min}$
- D)  $t = 597 \text{ min}$

### Problem 5

In a Jominy end-quench test performed on plain carbon steel, which of the following represents the sequence of microstructures observed from the quenched end of the specimen?

- A) Fine pearlite  $\rightarrow$  Coarse pearlite  $\rightarrow$  Martensite and pearlite  $\rightarrow$  Martensite
- B) Martensite  $\rightarrow$  Martensite and pearlite  $\rightarrow$  Fine pearlite  $\rightarrow$  Coarse pearlite
- C) Coarse pearlite  $\rightarrow$  Pearlite and martensite  $\rightarrow$  Fine pearlite  $\rightarrow$  Martensite
- D) Martensite  $\rightarrow$  Martensite and pearlite  $\rightarrow$  Coarse pearlite  $\rightarrow$  Fine pearlite

### Problem 6

Suppose we wish to investigate the hardenability of a steel containing 0.55 wt% C with an ASTM grain size of 6 and an alloy content of 0.4 wt% Mn, 0.15 wt% Si, and 0.3 wt% Cr. The steel is to be quenched in strongly agitated oil with quench severity  $H = 0.6$ . Determine the critical diameter.

- A)  $D_c = 0.15 \text{ in.}$
- B)  $D_c = 0.4 \text{ in.}$
- C)  $D_c = 0.65 \text{ in.}$
- D)  $D_c = 0.9 \text{ in.}$

## Problem 7

Which of the following options is the best combination of steel type and quenching regime to avoid the formation of cracks?

- A) Use a low-carbon steel and a fast rate of cooling.
- B) Use a low-carbon steel and a slow rate of cooling.
- C) Use a high-carbon steel and a fast rate of cooling.
- D) Use a high-carbon steel and a slow rate of cooling.

## Problem 8

When workpieces of heavy sections or of complicated shapes are heated, temperatures between 250°C and 600°C are particularly dangerous, because in this temperature range the steel does not have enough plasticity to compensate for thermal stresses. If thermal stresses are developed that overlap the strength of the material (which is substantially lower at higher temperatures), cracks will result. The tendency of a steel to crack depends on its chemical composition. Carbon content has a decisive influence: the higher the carbon content, the greater the sensitivity to cracking. The complex influence of carbon and other alloying elements is expressed by the following formula,

$$C_{ekv} = \frac{[C]+[Mn]}{5} + \frac{[Cr]}{4} + \frac{[Mo]}{3} + \frac{[Ni]}{10} + \frac{[V]}{5} + \frac{[Si]-0.5}{5} + \frac{[Ti]}{5} + \frac{[W]}{10} + \frac{[Al]}{10}$$

where the element symbols represent wt% content. The higher the calculated  $C_{ekv}$  value, the greater the sensitivity of the steel to cracking. The following value ranges are defined:

$C_{ekv} \leq 0.4$	The steel is not sensitive to cracking and can be heated quite rapidly.
$0.4 < C_{ekv} < 0.7$	The steel is medium sensitive to cracking.
$C_{ekv} \geq 0.7$	The steel is very sensitive to cracking (when heating up a preheating operation should be included).

Reconsider the steel with the composition introduced in Problem 6 - that is, a steel containing 0.55 wt% C, 0.4 wt% Mn, 0.15 wt% Si, and 0.3 wt% Cr. Calculate the value of  $C_{ekv}$  for this steel and evaluate its susceptibility to cracking.

- A)  $C_{ekv} = 0.2$  and the steel is not sensitive to cracking.
- B)  $C_{ekv} = 0.4$  and the steel is slightly sensitive to cracking.
- C)  $C_{ekv} = 0.6$  and the steel is medium sensitive to cracking.
- D)  $C_{ekv} = 0.8$  and the steel is highly sensitive to cracking.

## Problem 9

A steel part is being quenched in water. At the beginning of the quenching process, the steel has a thermal conductivity of 50 W/mK and the Grossmann number of the quenching process was determined to be 0.2. The interface heat transfer coefficient (W/m<sup>2</sup>K) is most nearly:

- A)  $h = 22$  W/m<sup>2</sup>K
- B)  $h = 70$  W/m<sup>2</sup>K
- C)  $h = 125$  W/m<sup>2</sup>K
- D)  $h = 141$  W/m<sup>2</sup>K

## Problem 10

Regarding quenching technology and other aspects of steel metallurgy, true or false?

- 1.( ) When a steel is quenched to room temperature after heat treatment, a portion of austenite will remain untransformed – the so-called retained austenite. In general, the greater the amount of carbon in the steel, the greater the amount of retained austenite after quenching.
- 2.( ) The primary requirement to be met by all quenchant media is that they should extract heat from the workpiece with good efficiency. They should yield proper cooling kinetics within the entire range of temperatures of interest in the quenching process – in particular, their cooling rates below  $M_s$  should be as high as possible so as to conduct the process quickly and effectively.

**3.( )** Agitation refers to liquid quenchant movement relative to the part. It is used to promote uniform quenching. Nonuniform quenching is associated with spotty hardness, increased surface cracking, and distortion.

**4.( )** Grossmann's H-value is used to characterize the quenching severity of cooling media. These values are stated relatively to the quenching severity factor of still brine at approximately 18°C, which is conventionally taken as unity.

**5.( )** Most alloying elements which enter into solid solution in austenite lower the martensitic start ( $M_s$ ) temperature, with the exception of cobalt and aluminum. The relative effect of some alloying elements can be described by the empirical equation

$$M_s (\text{°C}) = 539 - 423[C] - 30.4[\text{Mn}] - 17.7[\text{Ni}] - 12.1[\text{Cr}] - 7.5[\text{Mo}]$$

With reference to this formula, we conclude that the steel with the chemical composition proposed in Problem 6 will have a  $M_s$  temperature greater than 275°C.

**6.( )** The temperature at which bainite transformation starts is referred to as the  $B_s$  temperature. One equation for  $B_s$  for steels containing up to 0.55% carbon is.

$$B_s (\text{°C}) = 830 - 270[C] - 90[\text{Mn}] - 37[\text{Ni}] - 70[\text{Cr}] - 83[\text{Mo}]$$

The value of  $B_s$  for the steel introduced in Problem 6 is greater than 650°C.

**7.( )** Though not applicable to all situations, continuous cooling transformation (CCT) diagrams are quite versatile tools in the description of different cooling regimes of steel. For example, a single CCT diagram can be used to describe cooling regimes with discontinuous change in cooling rate, as in the case of a delayed quenching in air followed by a water or oil quenching.

**8.( )** The main gases used in vacuum furnaces for gas quenching are nitrogen, argon, helium, and hydrogen. In this group, hydrogen combines some of the best traits desired of a gaseous quenchant: it offers a high quenching power at a wide thermal range, it has no explosion hazard, and it protects the steel from decarburization at high temperatures.

**9.( )** Formerly, lead and its alloys with tin were the most often used metals for marquenching and austempering. However, since lead vapors are toxic and its quenching power does not greatly differ from that of molten salts, lead has been essentially abandoned as a cooling medium for these processes. One commonly used compound is saltpeter, which, despite being a reliable quenchant, must not be heated to exceedingly high temperatures since it may form exothermic, potentially explosive reactions.

**10.( )** In spray quenching, high pressure streams of liquid are directed through nozzles onto selected parts of the hot surface, thus allowing for localized cooling. Another advantage of this cooling method when compared to immersion quenching is that the degree of heat transfer across the surface can be controlled by varying the intensity of sprayed liquid.

## Problem 11

Considering a process of diffusional transformation of austenite to pearlite, the fraction transformed is measured at two different transformation times, giving the following results.

Transformation time (s)	Fraction transformed to pearlite, $f$
75	0.113
150	0.37

Assuming Avrami kinetics, the fraction transformed in 300 seconds is:

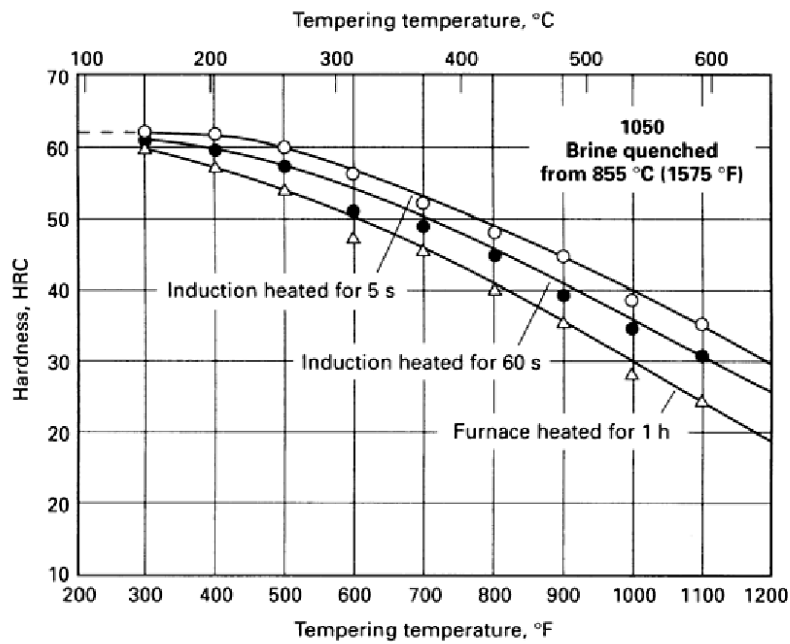
- A)  $f_{300} = 0.49$
- B)  $f_{300} = 0.62$
- C)  $f_{300} = 0.86$
- D)  $f_{300} = 0.95$

## Problem 12

The following figure displays the evolution of hardness as a function of temperature for 1050 steel austenitized at 1575°F and quenched in brine. As shown, the processes considered are furnace tempering for 1 hour, induction tempering for 5 seconds, and induction tempering for 60 seconds. The tempering parameter for any of these processes is given by

$$TP = \theta(14.44 + \log_{10} t)$$

where  $\theta$  is the temperature in degrees Rankine and  $t$  is time in seconds. Considering a hardness of 40 HRC, compute  $TP$  for 1-hour furnace tempering and for 5-second induction tempering. What do the results say about the relation between these processes?



## Problem 13

When a tensile steel specimen with a diameter of 0.608 in. and a gauge length of 2.0 in. was loaded to 10 kips, it was found that the gauge length was 2.45 in. Assuming the deformation was uniform, the true stress (psi) is most nearly:

- A)  $\sigma = 10,800$  psi
- B)  $\sigma = 21,100$  psi
- C)  $\sigma = 30,900$  psi
- D)  $\sigma = 42,300$  psi

## Problem 14

When a tensile steel specimen with a diameter of 0.608 in. and a gauge length of 2.0 in. was loaded to 10 kips, it was found that the gauge length was 2.45 in. Assuming the deformation was uniform, the true stress (psi) is most nearly:

- A)  $\sigma_Y = 285$  MPa
- B)  $\sigma_Y = 391$  MPa
- C)  $\sigma_Y = 471$  MPa
- D)  $\sigma_Y = 576$  Mpa

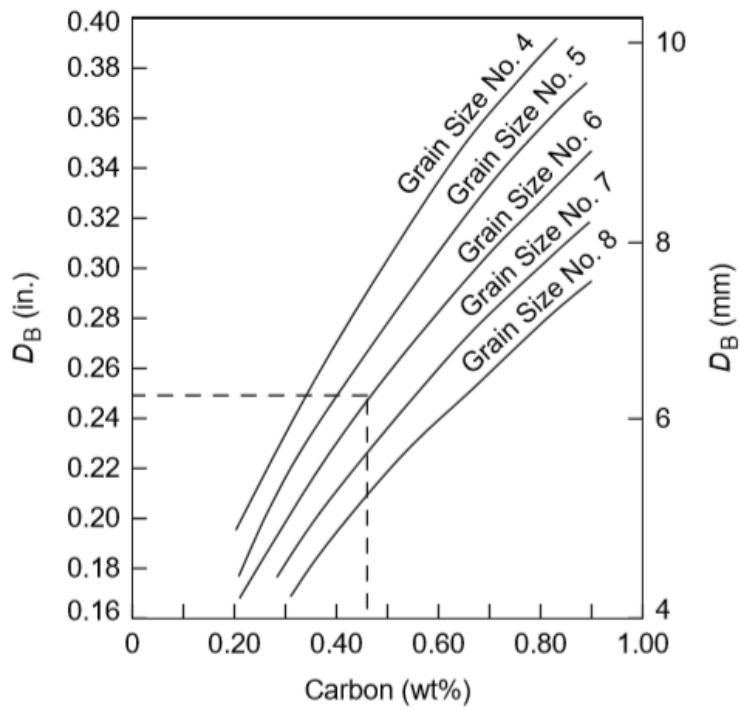
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## ADDITIONAL INFORMATION

**Table 1** Gaussian error function values

Z	erf (Z)	Z	erf (Z)	Z	erf (Z)
0	0	0.55	0.5633	1.3	0.9340
0.025	0.0282	0.60	0.6039	1.4	0.9523
0.05	0.0564	0.65	0.6420	1.5	0.9661
0.10	0.1125	0.70	0.6778	1.6	0.9763
0.15	0.1680	0.75	0.7112	1.7	0.9838
0.20	0.2227	0.80	0.7421	1.8	0.9891
0.25	0.2763	0.85	0.7707	1.9	0.9928
0.30	0.3286	0.90	0.7970	2.0	0.9953
0.35	0.3794	0.95	0.8209	2.2	0.9981
0.40	0.4284	1.0	0.8427	2.4	0.9993
0.45	0.4755	1.1	0.8802	2.6	0.9998
0.50	0.5205	1.2	0.9103	2.8	0.9999

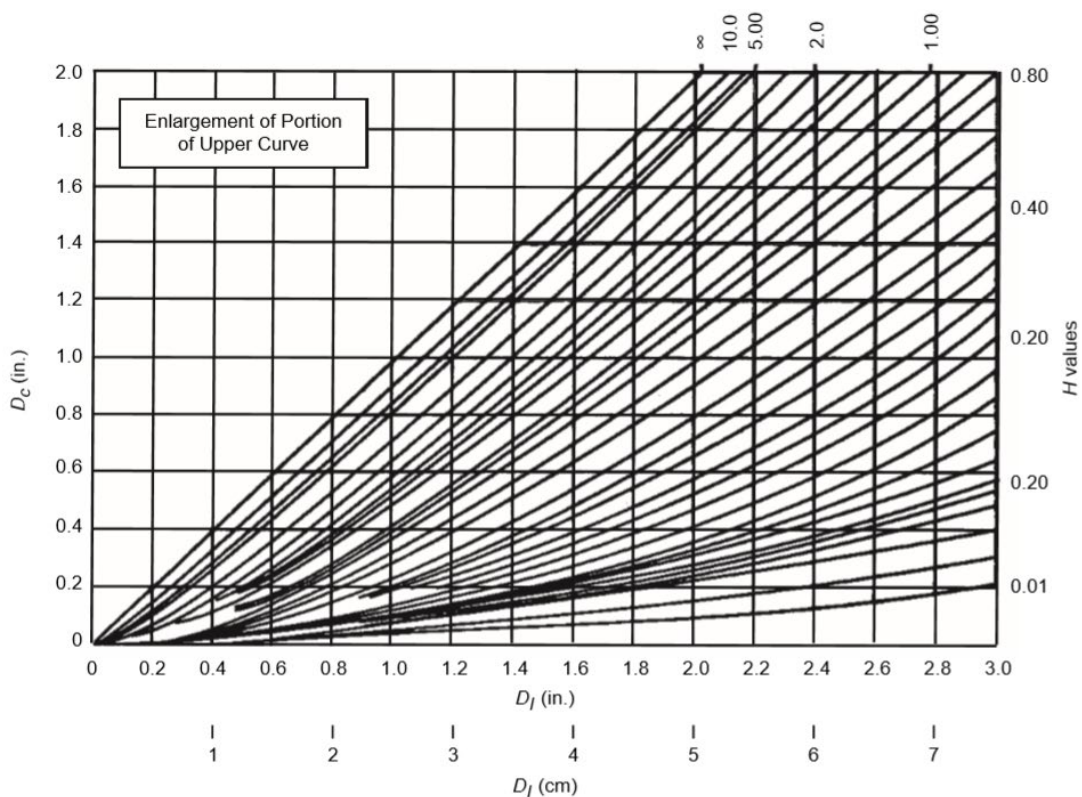
**Figure 1** Plot of base diameter,  $D_B$ , used in the calculation of ideal diameter.  
 (The value indicated by the dotted lines is not the value used in Problem 6)



**Table 2** Multiplying factors for alloying elements  
 (The values indicated by the dotted lines are not the values used in Problem 6)

Percent	Alloying element				
	Mn	Si	Ni	Cr	Mo
0.00	1.00	1.00	1.00	1.00	1.00
0.05	1.167	1.035	1.018	1.108	1.15
0.10	1.333	1.070	1.036	1.216	1.30
0.15	1.500	1.105	1.055	1.324	1.45
0.20	1.667	1.140	1.073	1.432	1.60
0.25	1.833	1.175	1.091	1.540	1.75
0.30	2.000	1.210	1.109	1.648	1.90
0.35	2.167	1.245	1.128	1.756	2.05
0.40	2.333	1.280	1.146	1.864	2.20
0.45	2.500	1.315	1.164	1.972	2.35
0.50	2.667	1.350	1.182	2.080	2.50
0.55	2.833	1.385	1.201	2.188	2.65
0.60	3.000	1.420	1.219	2.296	2.80
0.65	3.167	1.455	1.237	2.404	2.95
0.70	3.333	1.490	1.255	2.512	3.10
0.75	3.500	1.525	1.273	2.620	3.25
0.80	3.677	1.560	1.291	2.728	3.55
0.85	3.833	1.595	1.309	2.836	3.70
0.90	4.000	1.630	1.321	2.944	
0.95	4.167	1.665	1.345	3.052	
1.00	4.333	1.700	1.364	3.160	

**Figure 2** Relationship between ideal diameter and critical diameter.



## SOLUTIONS

### P.1 ■ Solution

Martensite has a body-centered tetragonal (bct) structure, austenite has a face-centered cubic (fcc) structure, and ferrite has a body-centered cubic (bcc) structure. Lastly, cementite has a complex orthorhombic crystal structure with 12 Fe atoms and 4 C atoms per unit cell. The correct sequence is P-3, Q-4, R-2, S-1.

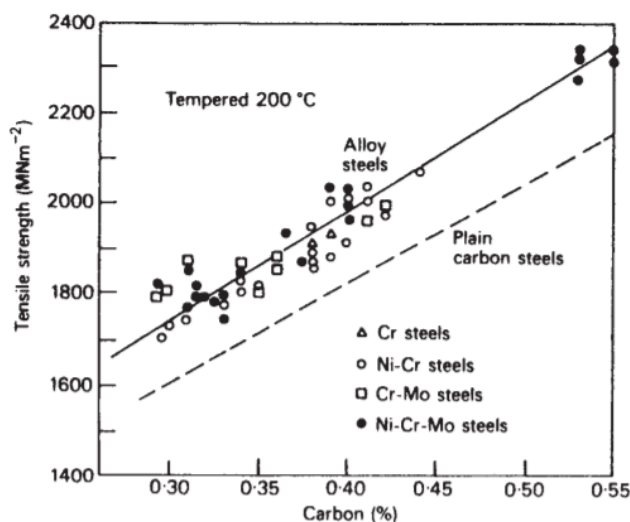
◆ The correct answer is **C**.

### P.2 ■ Solution

**1. True.** It is a fact that the hardenability of steel increases with increasing grain size, because the grain boundary area per unit volume decreases. The sites for nucleation of ferrite and pearlite are reduced in number, with the result that these transformations are slowed down and hardenability is increased correspondingly. The other main variable that affects hardenability is chemical composition; indeed, the most economical way of increasing the hardenability of plain carbon steel is to increase the manganese content, e.g., an increase from 0.60 to 1.40 wt%. Chromium and molybdenum are also effective.

**2. False.** Although it in fact applies to most steels, the Jominy end-quench test should not be used with highly alloyed steels that are hardened with the aid of air, since these steels harden not only by heat extraction through the quenched end but also by heat extraction by the surrounding air. This effect increases with increasing distance from the quenched end. Other than these restrictions, the method in question is suitable for most steels, except those of particularly low or high hardenability (i.e., steels with Grosmann ideal critical diameter  $D_I < 1.0$  in. or  $D_I > 6.0$  in.).

**3. True.** Indeed, the graph reveals that, in order to obtain really high strength levels in tempered steels, temper should be carried out at low temperatures, when the martensite is still heavily dislocated and the main strengthening dispersion is cementite or  $\epsilon$ -iron carbide. Alloy steels, when tempered in this range, not only provide very high tensile strengths with some ductility but are also superior to plain carbon steels; this is illustrated in the following graph, which is a comparison of mechanical properties of plain carbon and alloy steels tempered at 200°C.



**4. False.** Temper embrittlement can in fact be reversed by heating to over 600°C followed by rapid cooling. For the most part, simple plain carbon steels are not considered to be susceptible to temper embrittlement as long as manganese concentrations are held to below 0.5%. Alloy steels containing chromium and nickel are the most vulnerable. Additions of molybdenum at a concentration of up to 0.5% are effective in reducing the susceptibility of these steels to temper embrittlement. Molybdenum inhibits the segregation of impurities by readily precipitating as phosphides in the matrix.

**5. True.** Indeed, fuel-fired furnaces have a relevant fire/explosion hazard, and ventilation must be continuously employed to maintain an innocuous atmosphere and prevent the build-up of unwanted gases, such as carbon monoxide.

**6. False.** The effect of titanium, vanadium, aluminum, and especially boron in the hardenability of steel is decreased as the carbon content increases. Indeed, for carbon contents greater than about 0.9%, boron produces no measurable effect



on hardenability. Accordingly, boron alloying for the purpose of improving hardenability is only suitable for low-carbon steels. The statement also errs when it mentions that addition of boron in concentrations greater than, say, a thousandth of a percent will improve hardenability further.

**7. False.** The addition of the aforementioned elements to steel causes an additional hardening when the material is tempered at high temperatures, a phenomenon known as secondary hardening. Secondary hardening is caused by the formation of clusters of atoms of alloying elements and carbon and the replacement of relatively coarse particles of cementite by much more disperse precipitates of special carbides (TiC, VC, Mo<sub>2</sub>C, W<sub>2</sub>C).

**8. False.** For starters, the time at temperature is generally not critical inasmuch as a time for temperature homogenization and completion of austenitization is all that is required, *especially* in the case of geometrically simple parts. The ASM's *Heat Treater's Guide* recommends one hour at temperature, after a furnace has recovered, per inch of part thickness. The statement is correct when it mentions the increase in pearlite formation at higher cooling rates. However, the effect of additional pearlite and greater fineness is to increase, not reduce, strength and hardness. Lower cooling rates mean softer parts.

**9. True.** In accordance with the definition proposed in the statement, the degree of hardening is, in this case,

$$S = \frac{H_{\text{measured}}}{60\sqrt{[C]} + 20} = \frac{40}{60\sqrt{0.55} + 20} = 0.62$$

Since  $S < 0.7$ , we surmise that the part indeed does not meet the requirement for less stressed parts.

**10. True.** Indeed, flame hardening is especially applicable to parts in which only a small segment needs processing, or when the geometry of the part happens to be exceedingly complex for typical furnace heating and quenching (e.g., a large gear of complex design for which flame hardening of the teeth would not disturb the dimensions of the gear).

**11. False.** Vacuum carburization is performed at very low pressures, often no larger than 20 Torr, and that is the reason why the rate of flow of gas into the furnace is inevitably low. As a result, the carbon potential of the gas in deep recesses and blind holes is quickly depleted. The gas must be continuously replenished. If, in an effort to overcome these limitations, the gas pressure is increased substantially, another problem arises: the formation of free carbon, or sooting. Thus, in order to obtain cases of reasonably uniform depth over a part of complex shape, the gas pressure must be increased periodically to replenish the depleted atmosphere in recesses and then reduced again to the operating pressure. Clearly, a delicate balance exists in vacuum carburizing. Nevertheless, vacuum carburizing does have appreciable advantages, such as an excellent repeatability due to the degree of process control inherent in the process; improved mechanical properties due to a lack of intergranular oxidation; and reduced cycle times due to higher processing temperatures.

**12. False.** While it is true that nitrogen has a positive stabilization effect on austenite and martensite, the statement errs when it states that carbonitriding is performed at temperatures greater than those of carburization. In general, carbonitriding is performed at temperatures somewhat lower than those of carburization – say, in the range of 815 – 900°C in lieu of the temperatures of carburization, which often exceed 900°C. This ensures that ammonia does not decompose too fast and the nitrogen potential does not reach exceedingly high values, which would otherwise cause increased contents of retained austenite or even pores. Carbonitriding is also carried out for shorter times than typical carburization, and is generally restricted to the production of case depths no thicker than 0.5 mm. In these applications, use of carbonitriding is often more cost effective than ordinary carburization.

**13. False.** On the contrary, one of the goals of austempering is precisely to enable the formation of bainite, which would otherwise not occur if the steel were not maintained above  $M_s$  for a substantial period of time. In contrast, in martempering the steel is maintained at this temperature level in question for a lower period, just in time to prevent the formation of ferrite, pearlite and bainite.

**14. False.** This statement calls to mind an advantage of cold treatment over heat treatment: a cold treatment at temperatures somewhat below the

conventional temperature of  $-84^{\circ}\text{C}$  will not cause a reversal of the microstructure and mechanical properties obtained in the process, even if additional exposure occurs. Benefits from cold treatment range from enhancing transformation from austenite to martensite to improving the stress relief of castings and machined parts.

### P.3 ■ Solution

Martempering (or marquenching, to use a more appropriate term) is used when the goal is to form a microstructure with tempered martensite. Normalizing is carried out to conceive an uniform, fine-grained microstructure. A prolonged subcritical annealing produces spheroidized cementite in a ferrite matrix. Lastly, full annealing, a process aimed to softening a part and increasing the ductility for forming or machining, generally produces coarse grains of ferrite and pearlite. The correct sequence is P-3, Q-2, R-4, S-1.

◆ The correct answer is **D**.

### P.4 ■ Solution

A diffusion process such as the present one can be described by the relation

$$\frac{c_s - c_x}{c_s - c_o} = \text{erf}\left(\frac{x}{2\sqrt{Dt}}\right)$$

In the present case,

$$\frac{0.80 - 0.50}{0.80 - 0.20} = \text{erf}\left[\frac{(5 \times 10^{-4})}{2\sqrt{1.25 \times 10^{-11}t}}\right]$$

$$\therefore 0.5 = \text{erf}\left(\frac{70.7}{\sqrt{t}}\right)$$

Let  $Z = 70.7/t$ . Accordingly,

$$\text{erf } Z = 0.5$$

Referring to a table of error function values such as Table 1, we see that  $Z \approx 0.48$ . Thus,

$$Z = 0.48 \rightarrow \frac{70.7}{\sqrt{t}} = 0.48$$

$$\therefore t = \left(\frac{70.7}{0.48}\right)^2 = 21,700 \text{ s}$$

$$\therefore \boxed{t = 362 \text{ min}}$$

◆ The correct answer is **B**.

### P.5 ■ Solution

The sequence of microstructures observed from the quenched end of the specimen is Martensite  $\rightarrow$  Martensite and pearlite  $\rightarrow$  Fine pearlite  $\rightarrow$  Coarse pearlite.

◆ The correct answer is **B**.

### P.6 ■ Solution

Mapping a carbon content of 0.55 wt% and a grain size of 6 onto Figure 1, we read a base diameter of 0.27 in. The multiplication factors taken from Table 2 are 2.333 for 0.4 wt% Mn, 1.105 for 0.15 wt% Si, and 1.648 for 0.3 wt% Cr. The ideal diameter of a steel bar that will harden to 50% martensite when quenched in an ideal quench medium is given by

$$D_I = D_B \times M_f[\text{Mn}] \times M_f[\text{Si}] \times M_f[\text{Cr}]$$

$$\therefore D_I = 0.27 \times 2.333 \times 1.105 \times 1.648 = 1.15 \text{ in.}$$

However, the critical diameter also depends on quench severity. The relationship between ideal diameter and critical diameter for various quench

severities is given in Figure 2. With the ideal diameter calculated above and a quench severity  $H = 0.6$ , we read a critical diameter  $D_c = 0.4$  in.

◆ The correct answer is **B**.

### P.7 ■ Solution

The susceptibility of a steel to develop cracks, distortion, and warpage is directly proportional to the steel's carbon content and the rate of cooling.

◆ The correct answer is **B**.

### P.8 ■ Solution

All we have to do is apply the formula we were given,

$$C_{\text{ekv}} = \frac{0.55 + 0.4}{5} + \frac{0.3}{4} + \frac{0.15 - 0.5}{5} \approx \boxed{0.2}$$

Since  $C_{\text{ekv}} \leq 0.4$ , we conclude that the steel is not sensitive to cracking. A similar, slightly more straightforward relation for cracking propensity is the so-called carbon equivalent of Kunitake and Sisigawa (not to be confused with the carbon equivalent encountered in welding engineering), which is given by

$$C_{\text{eq}} = [C] + \frac{[\text{Mn}]}{5} + \frac{[\text{Mo}]}{5} + \frac{[\text{Cr}]}{10} + \frac{[\text{Ni}]}{10}$$

For the steel in question, we'd have

$$C_{\text{eq}} = 0.55 + \frac{0.40}{5} + \frac{0.30}{10} = 0.66$$

According to the authors, steels with  $0.52 < C_{\text{eq}} < 0.55$  are especially susceptible to cracking; the steel in question is not within this range.

◆ The correct answer is **A**.

### P.9 ■ Solution

The Grossmann number is given by

$$H = \frac{h}{2k}$$

where  $h$  is the convection heat transfer coefficient and  $k$  is the thermal conductivity of the metal. Solving for  $h$  and substituting, we obtain

$$H = \frac{h}{2k} \rightarrow h = 2kH$$

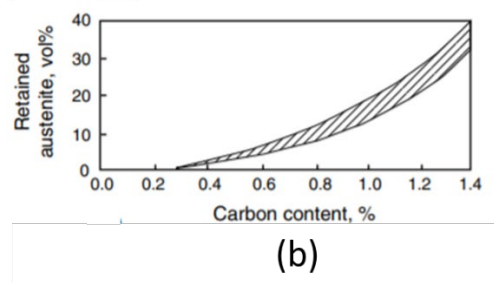
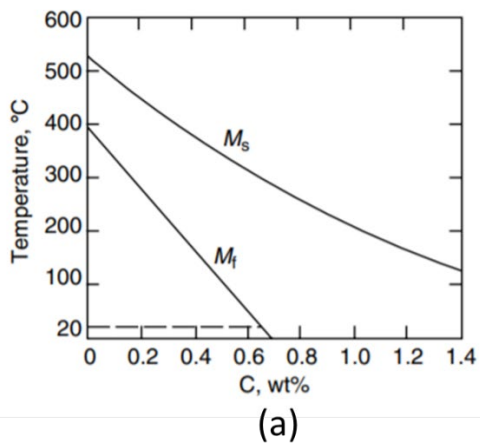
$$\therefore h = 2 \times 55 \times 0.2 = \boxed{22 \text{ W/m}^2\text{K}}$$

It is noteworthy that the use of a single, constant parameter – in this case, Grossmann's quenching severity factor  $H$  – to characterize a quenching medium is a rudimentary approximation at best. For one, the heat transfer coefficient changes very much during different stages of the quenching process; one investigator reports that, for a quenching oil at 150°C, the heat transfer coefficient during the boiling phase is about 5000 W/m<sup>2</sup>K, while at the convection phase it is only 350 W/m<sup>2</sup>K.

◆ The correct answer is **A**.

### P.10 ■ Solution

**1. True.** The greater the amount of carbon, the greater the amount of retained austenite will be. The martensite start ( $M_s$ ) and martensite finish ( $M_f$ ) temperatures for unalloyed steels depend on their carbon content, as shown in figure (a) below. As can be seen, when steels of more than 0.65% C are quenched the austenite-to-martensite transformation does not end at room temperature but at some lower temperature, even at temperatures much lower than 0°C. Consequently, after these steels are quenched to room temperature, a portion of austenite will remain untransformed – the so-called retained austenite. The amount of retained austenite is proportional to the carbon content, as shown in figure (b).



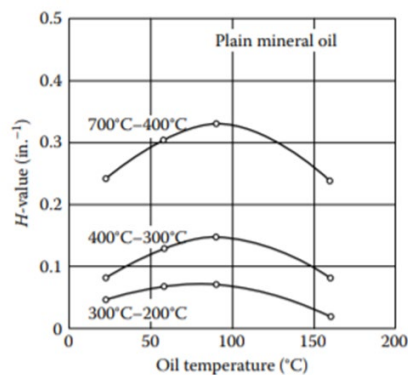
**2. False.** The cooling rate provided by the quenchant at the martensitic transformation temperature range should in fact be as low as possible. Low cooling rates produce minimal temperature gradients and allow the transformation to proceed almost simultaneously in the entire volume of the load, even when the quenched parts are considerably varied in size. This permits minimization of structural stresses.

**3. True.** Indeed, agitation is used to promote uniform quenching. Increasing agitation usually produces faster cooling rates in all three stages of heat removal by quenching (namely, the vapor blanket stage, the nucleate boiling stage, and the liquid cooling stage).

**4. False.** The H-value of still water, not brine, is taken as unity. Some values of *H* are summarized in the following table.

Degree of agitation	<i>H</i> -value (in. <sup>-2</sup> )		
	Oil	Water	Brine
No agitation	0.25 – 0.30	1.0	2.0
Mild agitation	0.30 – 0.35	1.0 – 1.1	2.2
Moderate agitation	0.35 – 0.40	1.1 – 1.3	
Strong agitation	0.40 – 0.80	1.3 – 2.0	5.0
Violent agitation	0.80 – 1.10	2.0 – 4.0	

As can be seen, the range of *H*-values for a given quenchant and degree of agitation can be quite wide. Another shortcoming of this approach is the fact that it does not consider variations in the thermophysical characteristics of the cooling medium, such as viscosity and concentration. For instance, the following graph shows that experimentally determined *H*-values for a plain mineral oil depend on the temperature of the liquid. Lastly, it should be realized that the degrees of agitation in the foregoing table are not uniformly or precisely defined. These are features of Grossmann's quenching severity factors, which are a somewhat imprecise method of assessment of quenching processes.



**5. True.** The steel in question contains 0.55 wt% C, 0.4 wt% Mn, 0.15 wt% Si, and 0.3 wt% Cr. Substituting in the empirical equation gives

$$M_s (^\circ\text{C}) = 539 - 423 \times 0.55 - 30.4 \times 0.4 - 12.1 \times 0.3 = 290.6^\circ\text{C}$$

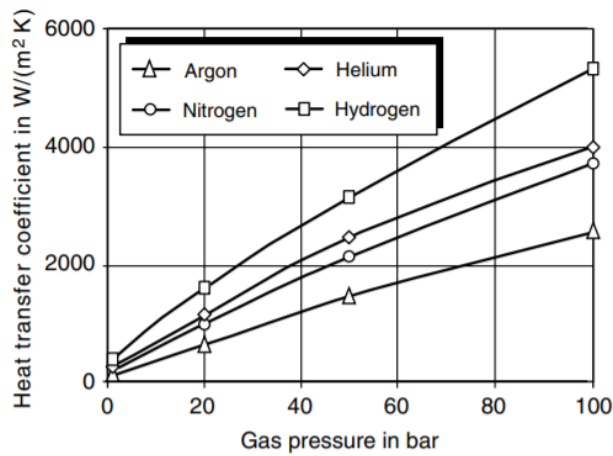
**6. False.** The value of  $B_s$  for the steel in question is

$$B_s (^\circ\text{C}) = 830 - 270 \times 0.55 - 90 \times 0.4 - 70 \times 0.3 = 625^\circ\text{C}$$

**7. False.** There are several quenching and heat treatment procedures in which the use of a single CCT diagram may not be suitable, including the

aforementioned discontinuous quenching procedure. The use of such diagrams is also questionable in the processing of carburized steel, in which, because of the big difference in carbon content between the core ( $\approx 0.2\%$ ) and the case ( $\approx 0.8\%$ ), the hardenability is different for each region and the pearlite and bainite regions may be shifted to much longer times. In such cases, a separate, unique diagram should be applied for the core and the case.

**8. False.** It is true that hydrogen has the highest cooling power of all gaseous quenchants – indeed, if the time required for hydrogen to cool from  $1000^\circ\text{C}$  to  $500^\circ\text{C}$  were assigned a value of unity, the corresponding values would be 1.37 for helium, 1.50 for nitrogen, and as much as 1.95 for argon. The following graph shows the heat transfer coefficients attained for each gas as a function of gas pressure (bar) for a cylinder with transverse gas flow. The statement becomes false, however, when it says that hydrogen has no explosion hazard (should air enter the furnace, a potentially explosive composition is formed) and that hydrogen may somehow protect steel from decarburization (at temperatures greater than  $1000^\circ\text{C}$ , it in fact exhibits decarburizing properties). Due to these drawbacks, hydrogen is rarely used as a gaseous quenchant, usually as an additive to nitrogen.



**9. True.** Indeed, lead has long been abandoned as a quenching medium because of its toxicity. Molten salts such as saltpeter have poor quenching power at first but can yield good performance by changing the agitation rate, adding water, or both. In spite of its fire hazard, saltpeter is a viable quenchant for parts with austenitizing temperatures lower than  $950^\circ\text{C}$  and section sizes no larger than 20 mm.

**10. True.** Indeed, spray quenching offers a better control of the heat transfer procedure than immersed quenching. However, spray quenching is more expensive and its effective application requires careful adaptation of the quenching nozzles to the geometry of the part.

### P.11 ■ Solution

From the Avrami equation, we can write

$$f = 1 - \exp(-kt^n)$$

Substituting the two data points yields

$$\begin{cases} 0.11 = 1 - \exp(-k \times 75^n) \\ 0.37 = 1 - \exp(-k \times 150^n) \end{cases}$$

which is a system of nonlinear equations in variables  $k$  and  $n$ . Solving it with a CAS such as Mathematica – for example, by using the Solve command with the Reals option activated – yields  $k = 2.19 \times 10^{-5}$  and  $n = 2.0$ . Equipped with these constants, we can determine the fraction transformed in 300 seconds, namely

$$f = 1 - \exp(-2.19 \times 10^{-5} \times 300^{2.0}) = \boxed{0.861}$$

Over four fifths of the austenite will have been transformed after 300 seconds.

◆ The correct answer is **C**.

### P.12 ■ Solution

The value of  $TP$  for 1-hour furnace tempering, with  $\theta = 800^\circ\text{F}$  read from the graph for the specified hardness level, is

$$TP = (800 + 460) \times (14.44 + \log_{10} 3600) = 22,700$$

Likewise, the value of  $TP$  for 5-second induction tempering, with  $\theta = 1000^\circ\text{F}$ , is

$$TP = (1000 + 460) \times (14.44 + \log_{10} 5) = 22,100$$

Since the tempering parameters are quite close to each other, the hardness and other mechanical properties yielded by the two treatments should be nearly the same. Heating time for processes may vary by up to three orders of magnitude; as a rule of thumb, typical heat times are approximately 1 s for laser hardening, 10 s for induction hardening, and 100 s for flame hardening.

### P.13 ■ Solution

The initial cross-sectional area of the specimen is  $A_0 = \pi \times 0.608^2/4 = 0.290 \text{ in.}^2$  and the engineering stress is

$$S = \frac{10,000}{0.290} = 34,500 \text{ psi}$$

The engineering strain is, in turn,

$$e = \frac{(2.45 - 2.0)}{2.0} = 0.225$$

The true stress follows as

$$\sigma = S(1 + e) = 34,500 \times (1 + 0.225) = \boxed{42,300 \text{ psi}}$$

◆ The correct answer is **D**.

### P.14 ■ Solution

Given the strain  $\varepsilon = \ln[1/(1 - 0.5)] = 0.693$ , the yield strength is calculated to be

$$\sigma_y = 620 \times 0.693^{0.2} = \boxed{576 \text{ MPa}}$$

◆ The correct answer is **D**.

## ANSWER SUMMARY

Problem 1	<b>C</b>
Problem 2	T/F
Problem 3	<b>D</b>
Problem 4	<b>B</b>
Problem 5	<b>B</b>
Problem 6	<b>B</b>
Problem 7	<b>B</b>
Problem 8	<b>A</b>
Problem 9	<b>A</b>
Problem 10	T/F
Problem 11	<b>C</b>
Problem 12	Open-ended pb.
Problem 13	<b>D</b>
Problem 14	<b>D</b>

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