SECTION 1
PROPERTIES OF STRUCTURAL STEELS AND EFFECTS OF STEELMAKING AND FABRICATION

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This section presents and discusses the properties of structural steels that are of importance in design and construction. Designers should be familiar with these properties so that they can select the most economical combination of suitable steels for each application and use the materials efficiently and safely.

In accordance with contemporary practice, the steels described in this section are given the names of the corresponding specifications of ASTM, 100 Barr Harbor Dr., West Conshohocken, PA, 19428. For example, all steels covered by ASTM A588, ''Specification for High-strength Low-alloy Structural Steel,'' are called A588 steel.

1.1 STRUCTURAL STEEL SHAPES AND PLATES

Steels for structural uses may be classified by chemical composition, tensile properties, and method of manufacture as carbon steels, high-strength low-alloy steels (HSLA), heat-treated carbon steels, and heat-treated constructional alloy steels. A typical stress-strain curve for a steel in each classification is shown in Fig. 1.1 to illustrate the increasing strength levels provided by the four classifications of steel. The availability of this wide range of specified minimum strengths, as well as other material properties, enables the designer to select an economical material that will perform the required function for each application.

Some of the most widely used steels in each classification are listed in Table 1.1 with their specified strengths in shapes and plates. These steels are weldable, but the welding materials and procedures for each steel must be in accordance with approved methods. Welding information for each of the steels is available from most steel producers and in publications of the American Welding Society.

1.1.1 Carbon Steels

A steel may be classified as a carbon steel if (1) the maximum content specified for alloying elements does not exceed the following: manganese—1.65%, silicon—0.60%, copper—

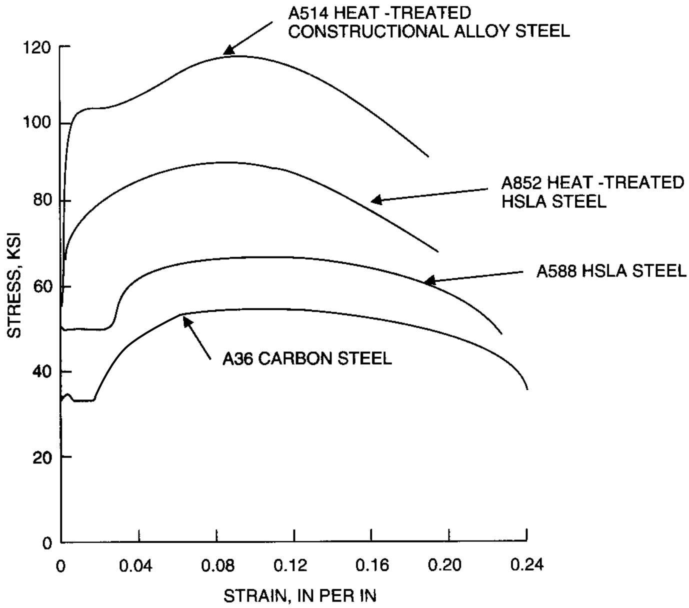

FIGURE 1.1 Typical stress-strain curves for structural steels. (Curves have been modified to reflect minimum specified properties.)

0.60%; (2) the specified minimum for copper does not exceed 0.40%; and (3) no minimum content is specified for other elements added to obtain a desired alloying effect.

A36 steel is the principal carbon steel for bridges, buildings, and many other structural uses. This steel provides a minimum yield point of 36 ksi in all structural shapes and in plates up to 8 in thick.

A573, the other carbon steel listed in Table 1.1, is available in three strength grades for plate applications in which improved notch toughness is important.

1.1.2 High-Strength Low-Alloy Steels

Those steels which have specified minimum yield points greater than 40 ksi and achieve that strength in the hot-rolled condition, rather than by heat treatment, are known as HSLA steels. Because these steels offer increased strength at moderate increases in price over carbon steels, they are economical for a variety of applications.

A242 steel is a **weathering steel,** used where resistance to atmospheric corrosion is of primary importance. Steels meeting this specification usually provide a resistance to atmospheric corrosion at least four times that of structural carbon steel. However, when required, steels can be selected to provide a resistance to atmospheric corrosion of five to eight times that of structural carbon steels. A specified minimum yield point of 50 ksi can be furnished in plates up to ¾ in thick and the lighter structural shapes. It is available with a lower yield point in thicker sections, as indicated in Table 1.1.

A588 is the primary weathering steel for structural work. It provides a 50-ksi yield point in plates up to 4 in thick and in all structural sections; it is available with a lower yield point in thicker plates. Several grades are included in the specification to permit use of various compositions developed by steel producers to obtain the specified properties. This steel provides about four times the resistance to atmospheric corrosion of structural carbon steels.

TABLE 1.1 Specified Minimum Properties for Structural Steel Shapes and Plates*

ASTM designation	Plate-thickness range, in	ASTM group for structural shapes†	Yield stress, ksi‡	Tensile strength, ksi‡	Elongation, % In 2 in§	Elongation, % In 8 in
A36	8 maximum	1–5	36	58–80	23–21	20
	over 8	1–5	32	58–80	23	20
A573						
Grade 58	1½ maximum	¶	32	58–71	24	21
Grade 65	1½ maximum	¶	35	65–77	23	20
Grade 70	1½ maximum	¶	42	70–90	21	18
High-strength low-alloy steels						
A242	¾ maximum	1 and 2	50	70	21	18
	Over ¾ to 1½ max	3	46	67	21	18
	Over 1½ to 4 max	4 and 5	42	63	21	18
A588	4 maximum	1–5	50	70	21	18
	Over 4 to 5 max	1–5	46	67	21	—
	Over 5 to 8 max	1–5	42	63	21	—
A572						
Grade 42	6 maximum	1–5	42	60	24	20
Grade 50	4 maximum	1–5	50	65	21	18
Grade 60	1¼ maximum	1–3	60	75	18	16
Grade 65	1¼ maximum	1–3	65	80	17	15
A992	¶	1–5	50–65	65	21	18
Heat-treated carbon and HSLA steels						
A633						
Grade A	4 maximum	¶	42	63–83	23	18
Grade C, D	2½ maximum	¶	50	70–90	23	18
	Over 2½ to 4 max	¶	46	65–85	23	18
Grade E	4 maximum	¶	60	80–100	23	18
	Over 4 to 6 max	¶	55	75–95	23	18
A678						
Grade A	1½ maximum	¶	50	70–90	22	—
Grade B	2½ maximum	¶	60	80–100	22	—
Grade C	¾ maximum	¶	75	95–115	19	—
	Over ¾ to 1½ max	¶	70	90–110	19	—
	Over 1½ to 2 max	¶	65	85–105	19	—
Grade D	3 maximum	¶	75	90–110	18	—
A852	4 maximum	¶	70	90–110	19	—
A913	¶	1–5	50	65	21	18
	¶	1–5	60	75	18	16
	¶	1–5	65	80	17	15
	¶	1–5	70	90	16	14

TABLE 1.1 Specified Minimum Properties for Structural Steel Shapes and Plates* (*Continued*)

ASTM designation	Plate-thickness range, in	ASTM group for structural shapes†	Yield stress, ksi‡	Tensile strength, ksi‡	Elongation, % In 2 in§	Elongation, % In 8 in
		Heat-treated constructional alloy steels				
A514	2½ maximum	¶	100	110–130	18	—
	Over 2½ to 6 max	¶	90	100–130	16	—

*The following are approximate values for all the steels:
Modulus of elasticity—29 × 10^3 ksi.
Shear modulus—11 × 10^3 ksi.
Poisson's ratio—0.30.
Yield stress in shear—0.57 times yield stress in tension.
Ultimate strength in shear—⅔ to ¾ times tensile strength.
Coefficient of thermal expansion—6.5 × 10^{-6} in per in per deg F for temperature range −50 to +150°F.
Density—490 lb/ft^3.
† See ASTM A6 for structural shape group classification.
‡ Where two values are shown for yield stress or tensile strength, the first is minimum and the second is maximum.
§ The minimum elongation values are modified for some thicknesses in accordance with the specification for the steel. Where two values are shown for the elongation in 2 in, the first is for plates and the second for shapes.
¶ Not applicable.

These relative corrosion ratings are determined from the slopes of corrosion-time curves and are based on carbon steels not containing copper. (The resistance of carbon steel to atmospheric corrosion can be doubled by specifying a minimum copper content of 0.20%.) Typical corrosion curves for several steels exposed to industrial atmosphere are shown in Fig. 1.2.

For methods of estimating the atmospheric corrosion resistance of low-alloy steels based on their chemical composition, see ASTM Guide G101. The A588 specification requires that the resistance index calculated according to Guide 101 shall be 6.0 or higher.

A588 and A242 steels are called **weathering steels** because, when subjected to alternate wetting and drying in most bold atmospheric exposures, they develop a tight oxide layer that substantially inhibits further corrosion. They are often used bare (unpainted) where the oxide finish that develops is desired for aesthetic reasons or for economy in maintenance. Bridges and exposed building framing are typical examples of such applications. Designers should investigate potential applications thoroughly, however, to determine whether a weathering steel will be suitable. Information on bare-steel applications is available from steel producers.

A572 specifies columbium-vanadium HSLA steels in four grades with minimum yield points of 42, 50, 60, and 65 ksi. Grade 42 in thicknesses up to 6 in and grade 50 in thicknesses up to 4 in are used for welded bridges. All grades may be used for riveted or bolted construction and for welded construction in most applications other than bridges.

A992 steel was introduced in 1998 as a new specification for rolled wide flange shapes for building framing. It provides a minimum yield point of 50 ksi, a maximum yield point of 65 ksi, and a maximum yield to tensile ratio of 0.85. These maximum limits are considered desirable attributes for seismic design. To enhance weldability, a maximum carbon equivalent is also included, equal to 0.47% for shape groups 4 and 5 and 0.45% for other groups. A supplemental requirement can be specified for an average Charpy V-notch toughness of 40 ft · lb at 70°F.

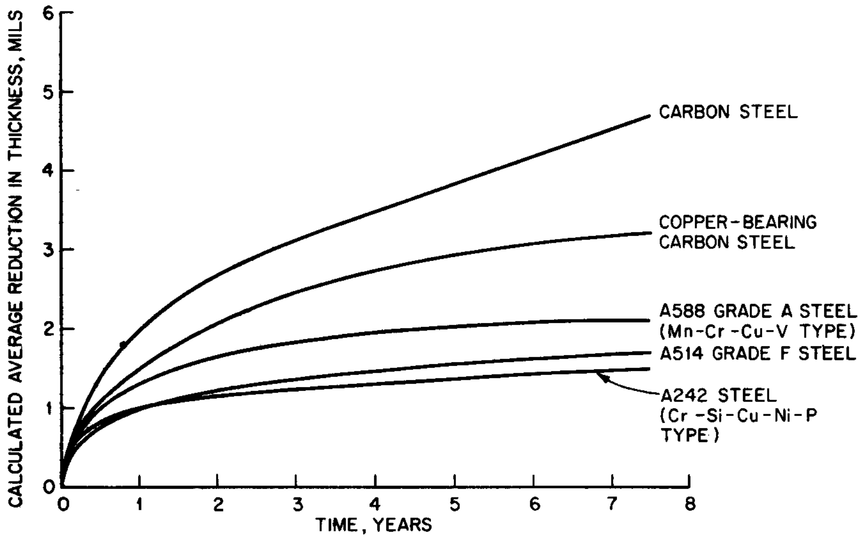

FIGURE 1.2 Corrosion curves for structural steels in an industrial atmosphere. (*From R. L. Brockenbrough and B. G. Johnston, USS Steel Design Manual, R. L. Brockenbrough & Associates, Inc., Pittsburgh, Pa., with permission.*)

1.1.3 Heat-Treated Carbon and HSLA Steels

Both carbon and HSLA steels can be heat treated to provide yield points in the range of 50 to 75 ksi. This provides an intermediate strength level between the as-rolled HSLA steels and the heat-treated constructional alloy steels.

A633 is a normalized HSLA plate steel for applications where improved notch toughness is desired. Available in four grades with different chemical compositions, the minimum yield point ranges from 42 to 60 ksi depending on grade and thickness.

A678 includes quenched-and-tempered plate steels (both carbon and HSLA compositions) with excellent notch toughness. It is also available in four grades with different chemical compositions; the minimum yield point ranges from 50 to 75 ksi depending on grade and thickness.

A852 is a quenched-and-tempered HSLA plate steel of the weathering type. It is intended for welded bridges and buildings and similar applications where weight savings, durability, and good notch toughness are important. It provides a minimum yield point of 70 ksi in thickness up to 4 in. The resistance to atmospheric corrosion is typically four times that of carbon steel.

A913 is a high-strength low-allow steel for structural shapes, produced by the quenching and self-tempering (QST) process. It is intended for the construction of buildings, bridges, and other structures. Four grades provide a minimum yield point of 50 to 70 ksi. Maximum carbon equivalents to enhance weldability are included as follows: Grade 50, 0.38%; Grade 60, 0.40%; Grade 65, 0.43%; and Grade 70, 0.45%. Also, the steel must provide an average Charpy V-notch toughness of 40 ft·lb at 70°F.

1.1.4 Heat-Treated Constructional Alloy Steels

Steels that contain alloying elements in excess of the limits for carbon steel and are heat treated to obtain a combination of high strength and toughness are termed **constructional**

alloy steels. Having a yield strength of 100 ksi, these are the strongest steels in general structural use.

A514 includes several grades of quenched and tempered steels, to permit use of various compositions developed by producers to obtain the specified strengths. Maximum thickness ranges from 1¼ to 6 in depending on the grade. Minimum yield strength for plate thicknesses over 2½ in is 90 ksi. Steels furnished to this specification can provide a resistance to atmospheric corrosion up to four times that of structural carbon steel depending on the grade.

Constructional alloy steels are also frequently selected because of their ability to resist abrasion. For many types of abrasion, this resistance is related to hardness or tensile strength. Therefore, constructional alloy steels may have nearly twice the resistance to abrasion provided by carbon steel. Also available are numerous grades that have been heat treated to increase the hardness even more.

1.1.5 Bridge Steels

Steels for application in bridges are covered by A709, which includes steel in several of the categories mentioned above. Under this specification, grades 36, 50, 70, and 100 are steels with yield strengths of 36, 50, 70, and 100 ksi, respectively. (See also Table 11.28.)

The grade designation is followed by the letter W, indicating whether ordinary or high atmospheric corrosion resistance is required. An additional letter, T or F, indicates that Charpy V-notch impact tests must be conducted on the steel. The T designation indicates that the material is to be used in a non-fracture-critical application as defined by AASHTO; the F indicates use in a fracture-critical application.

A trailing numeral, 1, 2, or 3, indicates the testing zone, which relates to the lowest ambient temperature expected at the bridge site. (See Table 1.2.) As indicated by the first footnote in the table, the service temperature for each zone is considerably less than the Charpy V-notch impact-test temperature. This accounts for the fact that the dynamic loading rate in the impact test is more severe than that to which the structure is subjected. The toughness requirements depend on fracture criticality, grade, thickness, and method of connection.

A709-HPS70W, designated as a High Performance Steel (HPS), is also now available for highway bridge construction. This is a weathering plate steel, designated HPS because it possesses superior weldability and toughness as compared to conventional steels of similar strength. For example, for welded construction with plates over 2½ in thick, A709-70W must have a minimum average Charpy V-notch toughness of 35 ft · lb at −10°F in Zone III, the most severe climate. Toughness values reported for some heats of A709-HPS70W have been much higher, in the range of 120 to 240 ft · lb at −10°F. Such extra toughness provides a very high resistance to brittle fracture.

(R. L. Brockenbrough, Sec. 9 in *Standard Handbook for Civil Engineers,* 4th ed., F. S. Merritt, ed., McGraw-Hill, Inc., New York.)

1.2 STEEL-QUALITY DESIGNATIONS

Steel plates, shapes, sheetpiling, and bars for structural uses—such as the load-carrying members in buildings, bridges, ships, and other structures—are usually ordered to the requirements of ASTM A6 and are referred to as **structural-quality steels.** (A6 does not indicate a specific steel.) This specification contains general requirements for delivery related to chemical analysis, permissible variations in dimensions and weight, permissible imperfections, conditioning, marking and tension and bend tests of a large group of structural steels. (Specific requirements for the chemical composition and tensile properties of these

TABLE 1.2 Charpy V-Notch Toughness for A709 Bridge Steels*

Grade	Maximum thickness, in, inclusive	Joining/fastening method	Minimum average energy, ft·lb	Test temperature, °F Zone 1	Test temperature, °F Zone 2	Test temperature, °F Zone 3
Non-fracture-critical members						
36T	4	Mech./Weld.	15	70	40	10
50T,† 50WT†	2	Mech./Weld.	15			
	2 to 4	Mechanical	15	70	40	10
	2 to 4	Welded	20			
70WT‡	2½	Mech./Weld.	20			
	2½ to 4	Mechanical	20	50	20	−10
	2½ to 4	Welded	25			
100T, 100WT	2½	Mech./Weld.	25			
	2½ to 4	Mechanical	25	30	0	−30
	2½ to 4	Welded	35			
Fracture-critical members						
36F	4	Mech./Weld.[a]	25	70	40	10
50F,† 50WF†	2	Mech./Weld.[a]	25	70	40	10
	2 to 4	Mechanical[a]	25	70	40	10
	2 to 4	Welded[b]	30	70	40	10
70WF‡	2½	Mech./Weld.[b]	30	50	20	−10
	2½ to 4	Mechanical[b]	30	50	20	−10
	2½ to 4	Welded[c]	35	50	20	−10
100F, 100WF	2½	Mech./Weld.[c]	35	30	0	−30
	2½ to 4	Mechanical[c]	35	30	0	−30
	2½ to 4	Welded[d]	45	30	0	NA

*Minimum **service** temperatures:
Zone 1, 0°F; Zone 2, below 0 to −30°F; Zone 3, below −30 to −60°F.
†If yield strength exceeds 65 ksi, reduce test temperature by 15°F for each 10 ksi above 65 ksi.
‡If yield strength exceeds 85 ksi, reduce test temperature by 15°F for each 10 ksi above 85 ksi.
[a] Minimum test value energy is 20 ft-lb.
[b] Minimum test value energy is 24 ft-lb.
[c] Minimum test value energy is 28 ft-lb.
[d] Minimum test value energy is 36 ft-lb.

steels are included in the specifications discussed in Art. 1.1.) All the steels included in Table 1.1 are structural-quality steels.

In addition to the usual die stamping or stenciling used for identification, plates and shapes of certain steels covered by A6 are marked in accordance with a color code, when specified by the purchaser, as indicated in Table 1.3.

Steel plates for pressure vessels are usually furnished to the general requirements of ASTM A20 and are referred to as **pressure-vessel-quality steels.** Generally, a greater number of mechanical-property tests and additional processing are required for pressure-vessel-quality steel.

TABLE 1.3 Identification Colors

Steels	Color	Steels	Color
A36	None	A913 grade 50	red and yellow
A242	Blue	A913 grade 60	red and gray
A514	Red	A913 grade 65	red and blue
A572 grade 42	Green and white	A913 grade 70	red and white
A572 grade 50	Green and yellow		
A572 grade 60	Green and gray		
A572 grade 65	Green and blue		
A588	Blue and yellow		
A852	Blue and orange		

1.3 RELATIVE COST OF STRUCTURAL STEELS

Because of the many strength levels and grades now available, designers usually must investigate several steels to determine the most economical one for each application. As a guide, relative material costs of several structural steels used as tension members, beams, and columns are discussed below. The comparisons are based on cost of steel to fabricators (steel producer's price) because, in most applications, cost of a steel design is closely related to material costs. However, the total fabricated and erected cost of the structure should be considered in a final cost analysis. Thus the relationships shown should be considered as only a general guide.

Tension Members. Assume that two tension members of different-strength steels have the same length. Then, their material-cost ratio C_2/C_1 is

$$\frac{C_2}{C_1} = \frac{A_2}{A_1}\frac{p_2}{p_1} \tag{1.1}$$

where A_1 and A_2 are the cross-sectional areas and p_1 and p_2 are the material prices per unit weight. If the members are designed to carry the same load at a stress that is a fixed percentage of the yield point, the cross-sectional areas are inversely proportional to the yield stresses. Therefore, their relative material cost can be expressed as

$$\frac{C_2}{C_1} = \frac{F_{y1}}{F_{y2}}\frac{p_2}{p_1} \tag{1.2}$$

where F_{y1} and F_{y2} are the yield stresses of the two steels. The ratio p_2/p_1 is the relative price factor. Values of this factor for several steels are given in Table 1.4, with A36 steel as the base. The table indicates that the relative price factor is always less than the corresponding yield-stress ratio. Thus the relative cost of tension members calculated from Eq. (1.2) favors the use of high-strength steels.

Beams. The optimal section modulus for an elastically designed I-shaped beam results when the area of both flanges equals half the total cross-sectional area of the member. Assume now two members made of steels having different yield points and designed to carry the same bending moment, each beam being laterally braced and proportioned for optimal

TABLE 1.4 Relative Price Factors*

Steel	Minimum yield stress, ksi	Relative price factor	Ratio of minimum yield stresses	Relative cost of tension members
A36	36	1.00	1.00	1.00
A572 grade 42	42	1.09	1.17	0.93
A572 grade 50	50	1.12	1.39	0.81
A588 grade A	50	1.23	1.39	0.88
A852	70	1.52	1.94	0.78
A514 grade B	100	2.07	2.78	0.75

*Based on plates ¾ × 96 × 240 in. Price factors for shapes tend to be lower. A852 and A514 steels are not available in shapes.

section modulus. Their relative weight W_2/W_1 and relative cost C_2/C_1 are influenced by the web depth-to-thickness ratio d/t. For example, if the two members have the same d/t values, such as a maximum value imposed by the manufacturing process for rolled beams, the relationships are

$$\frac{W_2}{W_1} = \left(\frac{F_{y1}}{F_{y2}}\right)^{2/3} \tag{1.3}$$

$$\frac{C_2}{C_1} = \frac{p_2}{p_1}\left(\frac{F_{y1}}{F_{y2}}\right)^{2/3} \tag{1.4}$$

If each of the two members has the maximum d/t value that precludes elastic web buckling, a condition of interest in designing fabricated plate girders, the relationships are

$$\frac{W_2}{W_1} = \left(\frac{F_{y1}}{F_{y2}}\right)^{1/2} \tag{1.5}$$

$$\frac{C_2}{C_1} = \frac{p_2}{p_1}\left(\frac{F_{y1}}{F_{y2}}\right)^{1/2} \tag{1.6}$$

Table 1.5 shows relative weights and relative material costs for several structural steels. These values were calculated from Eqs. (1.3) to (1.6) and the relative price factors given in Table 1.4, with A36 steel as the base. The table shows the decrease in relative weight with increase in yield stress. The relative material costs show that when bending members are thus compared for girders, the cost of A572 grade 50 steel is lower than that of A36 steel, and the cost of other steels is higher. For rolled beams, all the HSLA steels have marginally lower relative costs, and A572 grade 50 has the lowest cost.

Because the comparison is valid only for members subjected to the same bending moment, it does not indicate the relative costs for girders over long spans where the weight of the member may be a significant part of the loading. Under such conditions, the relative material costs of the stronger steels decrease from those shown in the table because of the reduction in girder weights. Also, significant economies can sometimes be realized by the use of hybrid girders, that is, girders having a lower-yield-stress material for the web than for the flange. HSLA steels, such as A572 grade 50, are often more economical for composite beams in

TABLE 1.5 Relative Material Cost for Beams

	Plate girders		Rolled beams	
Steel	Relative weight	Relative material cost	Relative weight	Relative material cost
A36	1.000	1.00	1.000	1.00
A572 grade 42	0.927	1.01	0.903	0.98
A572 grade 50	0.848	0.95	0.805	0.91
A588 grade A	0.848	1.04	0.805	0.99
A852	0.775	1.18		
A514 grade B	0.600	1.24		

the floors of buildings. Also, A588 steel is often preferred for bridge members in view of its greater durability.

Columns. The relative material cost for two columns of different steels designed to carry the same load may be expressed as

$$\frac{C_2}{C_1} = \frac{F_{c1}}{F_{c2}}\frac{p_2}{p_1} = \frac{F_{c1}/p_1}{F_{c2}/p_2} \tag{1.7}$$

where F_{c1} and F_{c2} are the column buckling stresses for the two members. This relationship is similar to that given for tension members, except that buckling stress is used instead of yield stress in computing the relative price-strength ratios. Buckling stresses can be calculated from basic column-strength criteria. (T. Y. Galambos, *Structural Stability Research Council Guide to Design Criteria for Metal Structures,* John Wiley & Sons, Inc., New York.) In general, the buckling stress is considered equal to the yield stress at a slenderness ratio L/r of zero and decreases to the classical Euler value with increasing L/r.

Relative price-strength ratios for A572 grade 50 and other steels, at L/r values from zero to 120 are shown graphically in Fig. 1.3. As before, A36 steel is the base. Therefore, ratios less than 1.00 indicate a material cost lower than that of A36 steel. The figure shows that for L/r from zero to about 100, A572 grade 50 steel is more economical than A36 steel. Thus the former is frequently used for columns in building construction, particularly in the lower stories, where slenderness ratios are smaller than in the upper stories.

1.4 STEEL SHEET AND STRIP FOR STRUCTURAL APPLICATIONS

Steel sheet and strip are used for many structural applications, including cold-formed members in building construction and the stressed skin of transportation equipment. Mechanical properties of several of the more frequently used sheet steels are presented in Table 1.6.

ASTM A570 covers seven strength grades of uncoated, hot-rolled, carbon-steel sheets and strip intended for structural use.

A606 covers high-strength, low-alloy, hot- and cold-rolled steel sheet and strip with enhanced corrosion resistance. This material is intended for structural or miscellaneous uses where weight savings or high durability are important. It is available, in cut lengths or coils, in either type 2 or type 4, with atmospheric corrosion resistance approximately two or four times, respectively, that of plain carbon steel.

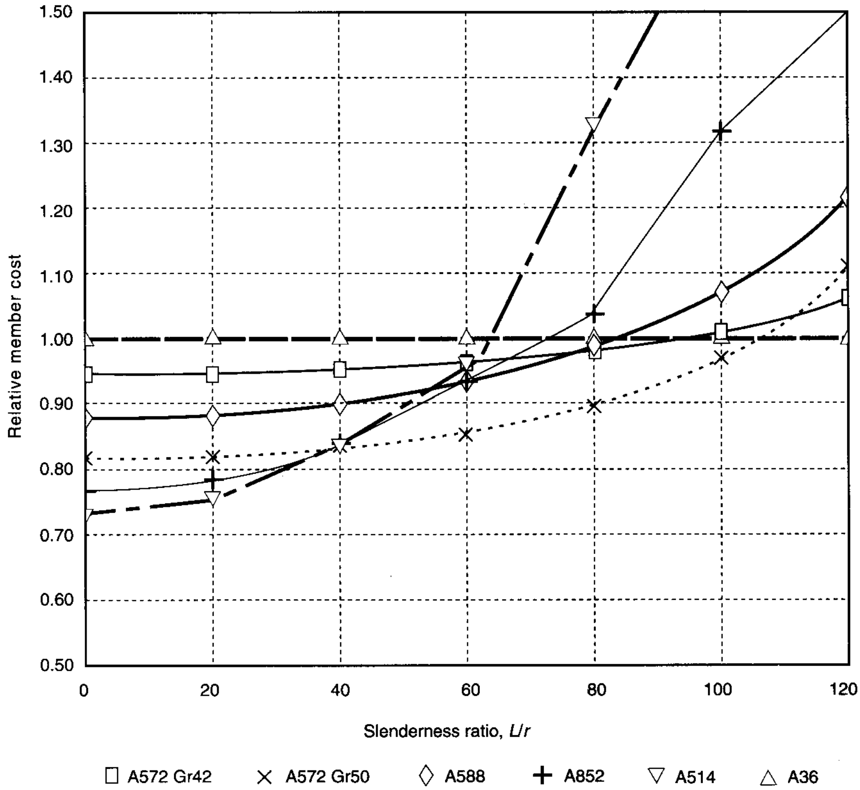

FIGURE 1.3 Curves show for several structural steels the variation of relative price-strength ratios, A36 steel being taken as unity, with slenderness ratios of compression members.

A607, available in six strength levels, covers high-strength, low-alloy columbium or vanadium, or both, hot- and cold-rolled steel sheet and strip. The material may be in either cut lengths or coils. It is intended for structural or miscellaneous uses where greater strength and weight savings are important. A607 is available in two classes, each with six similar strength levels, but class 2 offers better formability and weldability than class 1. Without addition of copper, these steels are equivalent in resistance to atmospheric corrosion to plain carbon steel. With copper, however, resistance is twice that of plain carbon steel.

A611 covers cold-rolled carbon sheet steel in coils and cut lengths. Four grades provide yield stress levels from 25 to 40 ksi. Also available is Grade E, which is a full-hard product with a minimum yield stress of 80 ksi but no specified minimum elongation.

A653 covers steel sheet, zinc coated (galvanized) or zinc-iron alloy coated (galvannealed) by the hot dip process in coils and cut lengths. Included are several grades of structural steel (SS) and high-strength low-alloy steel (HSLAS) with a yield stress of 33 to 80 ksi. HSLAS sheets are available as Type A, for applications where improved formability is important, and Type B for even better formability. The metallic coating is available in a wide range of coating weights, which provide excellent corrosion protection in many applications.

A715 provides for HSLAS, hot and cold-rolled, with improved formability over A606 an A607 steels. Yield stresses included range from 50 to 80 ksi.

A792 covers sheet in coils and cut lengths coated with aluminum-zinc alloy by the hot dip process. The coating is available in three coating weights, which provide both corrosion and heat resistance.

TABLE 1.6 Specified Minimum Mechanical Properties for Steel Sheet and Strip for Structural Applications

ASTM designation	Grade	Type of product	Yield point, ksi	Tensile strength, ksi	Elongation in 2 in, %*
A570		Hot-rolled			
	30		30	49	21
	33		33	52	18
	36		36	53	17
	40		40	55	15
	45		45	60	13
	50		50	65	11
	55		55	70	9
A606		Hot-rolled, cut length	50	70	22
		Hot-rolled, coils	45	65	22
		Cold-rolled	45	65	22
A607		Hot- or cold-rolled			
	45		45	60†	25–22
	50		50	65†	22–20
	55		55	70†	20–18
	60		60	75†	18–16
	65		65	80†	16–14
	70		70	85†	14–12
A611		Cold-rolled			
	A		25	42	26
	B		30	45	24
	C		33	48	22
	D		40	52	20
A653**		Galvanized or galvannealed			
	SS 33		33	45	20
	SS 37		37	52	18
	SS 40		40	55	16
	SS 50, class 1		50	65	12
	SS 50, class 2		50	70	12
	HSLAS 50		50	60	20–22
	HSLAS 50		60	70	16–18
	HSLAS 50		70	80	12–14
	HSLAS 50		80	90	10–12
A715		Hot- and cold-rolled			
	50		50	60	22
	60		60	70	18
	70		70	80	16
	80		80	90	14
A792		Aluminum-zinc alloy coated			
	SS 33		33	45	20
	SS 37		37	52	18
	SS 40		40	55	16
	SS 50A		50	65	12

*Modified for some thicknesses in accordance with the specification. For A607, where two values are given, the first is for hot-rolled, the second for cold-rolled steel. For A653, where two values are given, the first is for type A product, the second for type B.

†For class 1 product. Reduce tabulated strengths 5 ksi for class 2.

**Also available as A875 with zinc-5% aluminum alloy coating.

1.5 TUBING FOR STRUCTURAL APPLICATIONS

Structural tubing is being used more frequently in modern construction (Art. 6.30). It is often preferred to other steel members when resistance to torsion is required and when a smooth, closed section is aesthetically desirable. In addition, structural tubing often may be the economical choice for compression members subjected to moderate to light loads. Square and rectangular tubing is manufactured either by cold or hot forming welded or seamless round tubing in a continuous process. A500 cold-formed carbon-steel tubing (Table 1.7) is produced in four strength grades in each of two product forms, shaped (square or rectangular) or round. A minimum yield point of up to 50 ksi is available for shaped tubes and up to 46 ksi for round tubes. A500 grade B and grade C are commonly specified for building construction applications and are available from producers and steel service centers.

A501 tubing is a hot-formed carbon-steel product. It provides a yield point equal to that of A36 steel in tubing having a wall thickness of 1 in or less.

A618 tubing is a hot-formed HSLA product that provides a minimum yield point of up to 50 ksi. The three grades all have enhanced resistance to atmospheric corrosion. Grades Ia and Ib can be used in the bare condition for many applications when properly exposed to the atmosphere.

A847 tubing covers cold-formed HSLA tubing and provides a minimum yield point of 50 ksi. It also offers enhanced resistance to atmospheric corrosion and, when properly exposed, can be used in the bare condition for many applications.

1.6 STEEL CABLE FOR STRUCTURAL APPLICATIONS

Steel cables have been used for many years in bridge construction and are occasionally used in building construction for the support of roofs and floors. The types of cables used for

TABLE 1.7 Specified Minimum Mechanical Properties of Structural Tubing

ASTM designation	Product form	Yield point, ksi	Tensile strength, ksi	Elongation in 2 in, %
A500	Shaped			
Grade A		39	45	25
Grade B		46	58	23
Grade C		50	62	21
Grade D		36	58	23
A500	Round			
Grade A		33	45	25
Grade B		42	58	23
Grade C		46	62	21
Grade D		36	58	23
A501	Round or shaped	36	58	23
A618	Round or shaped			
Grades Ia, lb, II				
Walls $\leq$3/4 in		50	70	22
Walls $>$3/4 to 1½ in		46	67	22
Grade III		50	65	20
A847	Round or shaped	50	70	19

TABLE 1.8 Mechanical Properties of Steel Cables

Minimum breaking strength, kip,* of selected cable sizes			Minimum modulus of elasticity, ksi,* for indicated diameter range	
Nominal diameter, in	Zinc-coated strand	Zinc-coated rope	Nominal diameter range, in	Minimum modulus, ksi
½	30	23	Prestretched	
¾	68	52	zinc-coated strand	
1	122	91.4	½ to 2 9⁄16	24,000
1½	276	208	2 5⁄8 and over	23,000
2	490	372	Prestretched	
3	1076	824	zinc-coated rope	
4	1850	1460	3⁄8 to 4	20,000

* Values are for cables with class A zinc coating on all wires. Class B or C can be specified where additional corrosion protection is required.

these applications are referred to as **bridge strand** or **bridge rope.** In this use, **bridge** is a generic term that denotes a specific type of high-quality strand or rope.

A **strand** is an arrangement of wires laid helically about a center wire to produce a symmetrical section. A **rope** is a group of strands laid helically around a core composed of either a strand or another wire rope. The term **cable** is often used indiscriminately in referring to wires, strands, or ropes. Strand may be specified under ASTM A586; wire rope, under A603.

During manufacture, the individual wires in bridge strand and rope are generally galvanized to provide resistance to corrosion. Also, the finished cable is prestretched. In this process, the strand or rope is subjected to a predetermined load of not more than 55% of the breaking strength for a sufficient length of time to remove the ''structural stretch'' caused primarily by radial and axial adjustment of the wires or strands to the load. Thus, under normal design loadings, the elongation that occurs is essentially elastic and may be calculated from the elastic-modulus values given in Table 1.8.

Strands and ropes are manufactured from cold-drawn wire and do not have a definite yield point. Therefore, a working load or design load is determined by dividing the specified minimum breaking strength for a specific size by a suitable safety factor. The breaking strengths for selected sizes of bridge strand and rope are listed in Table 1.8.

1.7 TENSILE PROPERTIES

The tensile properties of steel are generally determined from tension tests on small specimens or coupons in accordance with standard ASTM procedures. The behavior of steels in these tests is closely related to the behavior of structural-steel members under static loads. Because, for structural steels, the yield points and moduli of elasticity determined in tension and compression are nearly the same, compression tests are seldom necessary.

Typical tensile stress-strain curves for structural steels are shown in Fig. 1.1. The initial portion of these curves is shown at a magnified scale in Fig. 1.4. Both sets of curves may be referred to for the following discussion.

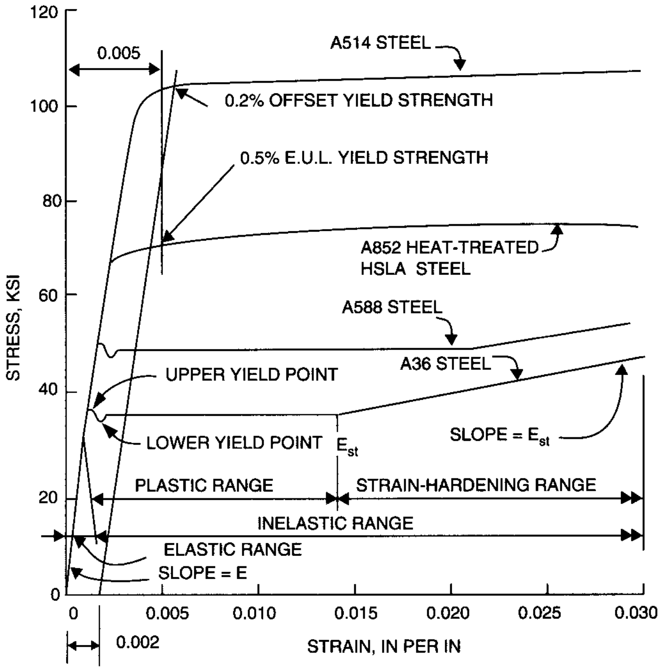

FIGURE 1.4 Partial stress-strain curves for structural steels strained through the plastic region into the strain-hardening range. (*From R. L. Brockenbrough and B. G. Johnston, USS Steel Design Manual, R. L. Brockenbrough & Associates, Inc., Pittsburgh, Pa., with permission.*)

Strain Ranges. When a steel specimen is subjected to load, an initial **elastic range** is observed in which there is no permanent deformation. Thus, if the load is removed, the specimen returns to its original dimensions. The ratio of stress to strain within the elastic range is the **modulus of elasticity,** or **Young's modulus** E. Since this modulus is consistently about 29×10^3 ksi for all the structural steels, its value is not usually determined in tension tests, except in special instances.

The strains beyond the elastic range in the tension test are termed the **inelastic range.** For as-rolled and high-strength low-alloy (HSLA) steels, this range has two parts. First observed is a **plastic range,** in which strain increases with no appreciable increase in stress. This is followed by a **strain-hardening range,** in which strain increase is accompanied by a significant increase in stress. The curves for heat-treated steels, however, do not generally exhibit a distinct plastic range or a large amount of strain hardening.

The strain at which strain hardening begins (ϵ_{st}) and the rate at which stress increases with strain in the strain-hardening range (the strain-hardening modulus E_{st}) have been determined for carbon and HSLA steels. The average value of E_{st} is 600 ksi, and the length of the yield plateau is 5 to 15 times the yield strain. (T. V. Galambos, "Properties of Steel for Use in LRFD," *Journal of the Structural Division, American Society of Civil Engineers,* Vol. 104, No. ST9, 1978.)

Yield Point, Yield Strength, and Tensile Strength. As illustrated in Fig. 1.4, carbon and HSLA steels usually show an upper and lower yield point. The upper yield point is the value usually recorded in tension tests and thus is simply termed the **yield point.**

The heat-treated steels in Fig. 1.4, however, do not show a definite yield point in a tension test. For these steels it is necessary to define a **yield strength,** the stress corresponding to a specified deviation from perfectly elastic behavior. As illustrated in the figure, yield strength is usually specified in either of two ways: For steels with a specified value not exceeding 80 ksi, yield strength is considered as the stress at which the test specimen reaches a 0.5% extension under load (0.5% EUL) and may still be referred to as the yield point. For higher-strength steels, the yield strength is the stress at which the specimen reaches a strain 0.2% greater than that for perfectly elastic behavior.

Since the amount of inelastic strain that occurs before the yield strength is reached is quite small, yield strength has essentially the same significance in design as yield point. These two terms are sometimes referred to collectively as **yield stress.**

The maximum stress reached in a tension test is the tensile strength of the steel. After this stress is reached, increasing strains are accompanied by decreasing stresses. Fracture eventually occurs.

Proportional Limit. The proportional limit is the stress corresponding to the first visible departure from linear-elastic behavior. This value is determined graphically from the stress-strain curve. Since the departure from elastic action is gradual, the proportional limit depends greatly on individual judgment and on the accuracy and sensitivity of the strain-measuring devices used. The proportional limit has little practical significance and is not usually recorded in a tension test.

Ductility. This is an important property of structural steels. It allows redistribution of stresses in continuous members and at points of high local stresses, such as those at holes or other discontinuities.

In a tension test, ductility is measured by percent elongation over a given gage length or percent reduction of cross-sectional area. The percent elongation is determined by fitting the specimen together after fracture, noting the change in gage length and dividing the increase by the original gage length. Similarly, the percent reduction of area is determined from cross-sectional measurements made on the specimen before and after testing.

Both types of ductility measurements are an index of the ability of a material to deform in the inelastic range. There is, however, no generally accepted criterion of minimum ductility for various structures.

Poisson's Ratio. The ratio of transverse to longitudinal strain under load is known as **Poisson's ratio** ν. This ratio is about the same for all structural steels—0.30 in the elastic range and 0.50 in the plastic range.

True-Stress–True-Strain Curves. In the stress-strain curves shown previously, stress values were based on original cross-sectional area, and the strains were based on the original gauge length. Such curves are sometimes referred to as **engineering-type stress-strain curves.** However, since the original dimensions change significantly after the initiation of yielding, curves based on instantaneous values of area and gage length are often thought to be of more fundamental significance. Such curves are known as **true-stress–true-strain curves.** A typical curve of this type is shown in Fig. 1.5.

The curve shows that when the decreased area is considered, the true stress actually increases with increase in strain until fracture occurs instead of decreasing after the tensile strength is reached, as in the engineering stress-strain curve. Also, the value of true strain at fracture is much greater than the engineering strain at fracture (though until yielding begins true strain is less than engineering strain).

1.8 PROPERTIES IN SHEAR

The ratio of shear stress to shear strain during initial elastic behavior is the **shear modulus** G. According to the theory of elasticity, this quantity is related to the modulus of elasticity E and Poisson's ratio ν by

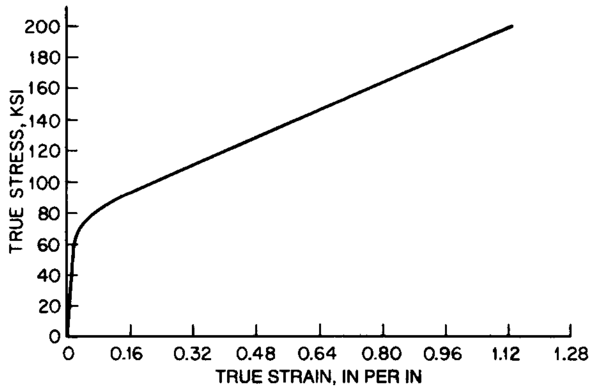

FIGURE 1.5 Curve shows the relationship between true stress and true strain for 50-ksi yield-point HSLA steel.

$$G = \frac{E}{2(1 + \nu)} \tag{1.8}$$

Thus a minimum value of G for structural steels is about 11×10^3 ksi. The yield stress in shear is about 0.57 times the yield stress in tension. The shear strength, or shear stress at failure in pure shear, varies from two-thirds to three-fourths the tensile strength for the various steels. Because of the generally consistent relationship of shear properties to tensile properties for the structural steels, and because of the difficulty of making accurate shear tests, shear tests are seldom performed.

1.9 HARDNESS TESTS

In the Brinell hardness test, a small spherical ball of specified size is forced into a flat steel specimen by a known static load. The diameter of the indentation made in the specimen can be measured by a micrometer microscope. The **Brinell hardness number** may then be calculated as the ratio of the applied load, in kilograms, to the surface area of the indentation, in square millimeters. In practice, the hardness number can be read directly from tables for given indentation measurements.

The Rockwell hardness test is similar in principle to the Brinell test. A spheroconical diamond penetrator is sometimes used to form the indentation and the depth of the indentation is measured with a built-in, differential depth-measurement device. This measurement, which can be read directly from a dial on the testing device, becomes the **Rockwell hardness number.**

In either test, the hardness number depends on the load and type of penetrator used; therefore, these should be indicated when listing a hardness number. Other hardness tests, such as the Vickers tests, are also sometimes used. Tables are available that give approximate relationships between the different hardness numbers determined for a specific material.

Hardness numbers are considered to be related to the tensile strength of steel. Although there is no absolute criterion to convert from hardness numbers to tensile strength, charts are available that give approximate conversions (see ASTM A370). Because of its simplicity, the hardness test is widely used in manufacturing operations to estimate tensile strength and to check the uniformity of tensile strength in various products.

1.10 EFFECT OF COLD WORK ON TENSILE PROPERTIES

In the fabrication of structures, steel plates and shapes are often formed at room temperatures into desired shapes. These cold-forming operations cause inelastic deformation, since the steel retains its formed shape. To illustrate the general effects of such deformation on strength and ductility, the elemental behavior of a carbon-steel tension specimen subjected to plastic deformation and subsequent tensile reloadings will be discussed. However, the behavior of actual cold-formed structural members is more complex.

As illustrated in Fig. 1.6, if a steel specimen is unloaded after being stressed into either the plastic or strain-hardening range, the unloading curve follows a path parallel to the elastic portion of the stress-strain curve. Thus a residual strain, or **permanent set,** remains after the load is removed. If the specimen is promptly reloaded, it will follow the unloading curve to the stress-strain curve of the virgin (unstrained) material.

If the amount of plastic deformation is less than that required for the onset of strain hardening, the yield stress of the plastically deformed steel is about the same as that of the virgin material. However, if the amount of plastic deformation is sufficient to cause strain hardening, the yield stress of the steel is larger. In either instance, the tensile strength remains the same, but the ductility, measured from the point of reloading, is less. As indicated in Fig. 1.6, the decrease in ductility is nearly equal to the amount of inelastic prestrain.

A steel specimen that has been strained into the strain-hardening range, unloaded, and allowed to age for several days at room temperature (or for a much shorter time at a moderately elevated temperature) usually shows the behavior indicated in Fig. 1.7 during reloading. This phenomenon, known as **strain aging,** has the effect of increasing yield and tensile strength while decreasing ductility.

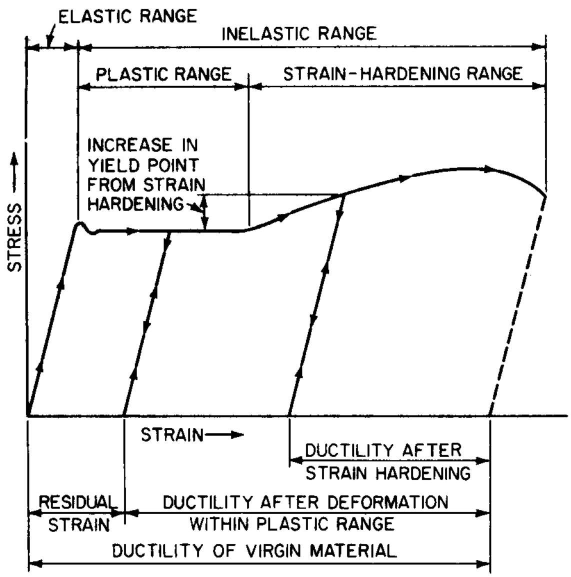

FIGURE 1.6 Stress-strain diagram (not to scale) illustrating the effects of strain-hardening steel. (*From R. L. Brockenbrough and B. G. Johnston, USS Steel Design Manual, R. L. Brockenbrough & Associates, Inc., Pittsburgh, Pa., with permission.*)

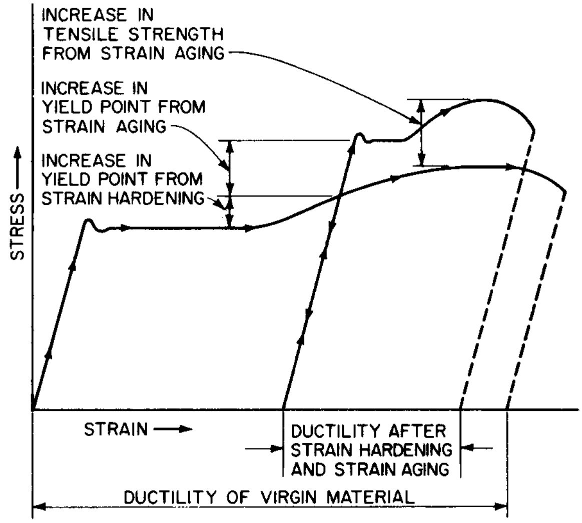

FIGURE 1.7 Effects of strain aging are shown by stress-strain diagram (not to scale). (*From R. L. Brockenbrough and B. G. Johnston, USS Steel Design Manual, R. L. Brockenbrough & Associates, Inc., Pittsburgh, Pa., with permission.*)

Most of the effects of cold work on the strength and ductility of structural steels can be eliminated by thermal treatment, such as stress relieving, normalizing, or annealing. However, such treatment is not often necessary.

(G. E. Dieter, Jr., *Mechanical Metallurgy,* 3rd ed., McGraw-Hill, Inc., New York.)

1.11 EFFECT OF STRAIN RATE ON TENSILE PROPERTIES

Tensile properties of structural steels are usually determined at relatively slow strain rates to obtain information appropriate for designing structures subjected to static loads. In the design of structures subjected to high loading rates, such as those caused by impact loads, however, it may be necessary to consider the variation in tensile properties with strain rate.

Figure 1.8 shows the results of rapid tension tests conducted on a carbon steel, two HSLA steels, and a constructional alloy steel. The tests were conducted at three strain rates and at three temperatures to evaluate the interrelated effect of these variables on the strength of the steels. The values shown for the slowest and the intermediate strain rates on the room-temperature curves reflect the usual room-temperature yield stress and tensile strength, respectively. (In determination of yield stress, ASTM E8 allows a maximum strain rate of $\frac{1}{16}$ in per in per mm, or 1.04×10^{-3} in per in per sec. In determination of tensile strength, E8 allows a maximum strain rate of 0.5 in per in per mm, or 8.33×10^{-3} in per in per sec.)

The curves in Fig. 1.8*a* and *b* show that the tensile strength and 0.2% offset yield strength of all the steels increase as the strain rate increases at −50°F and at room temperature. The greater increase in tensile strength is about 15%, for A514 steel, whereas the greatest increase in yield strength is about 48%, for A515 carbon steel. However, Fig. 1.8*c* shows that at 600°F, increasing the strain rate has a relatively small influence on the yield strength. But a faster strain rate causes a slight decrease in the tensile strength of most of the steels.

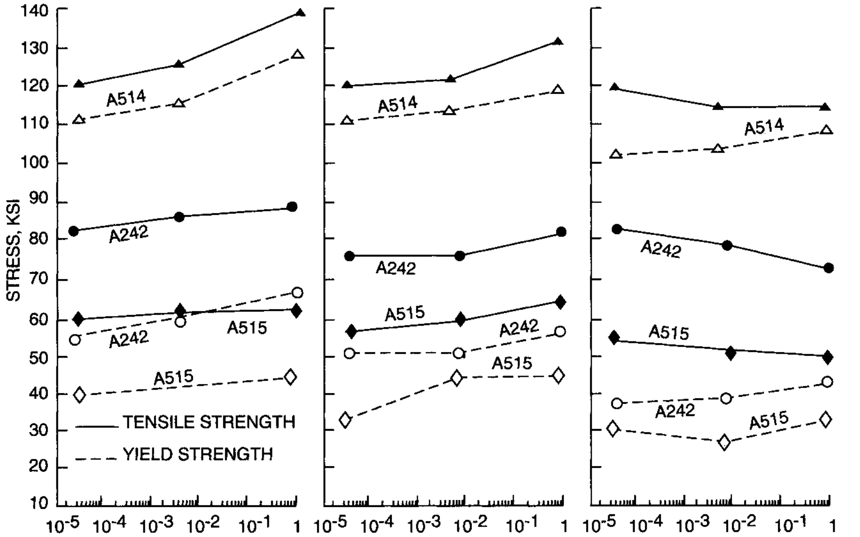

FIGURE 1.8 Effects of strain rate on yield and tensile strengths of structural steels at low, normal, and elevated temperatures. (*From R. L. Brockenbrough and B. G. Johnston, USS Steel Design Manual, R. L. Brockenbrough & Associates, Inc., Pittsburgh, Pa., with permission.*)

Ductility of structural steels, as measured by elongation or reduction of area, tends to decrease with strain rate. Other tests have shown that modulus of elasticity and Poisson's ratio do not vary significantly with strain rate.

1.12 EFFECT OF ELEVATED TEMPERATURES ON TENSILE PROPERTIES

The behavior of structural steels subjected to short-time loadings at elevated temperatures is usually determined from short-time tension tests. In general, the stress-strain curve becomes more rounded and the yield strength and tensile strength are reduced as temperatures are increased. The ratios of the elevated-temperature value to room-temperature value of yield and tensile strengths of several structural steels are shown in Fig. 1.9*a* and *b*, respectively.

Modulus of elasticity decreases with increasing temperature, as shown in Fig. 1.9*c*. The relationship shown is nearly the same for all structural steels. The variation in shear modulus with temperature is similar to that shown for the modulus of elasticity. But Poisson's ratio does not vary over this temperature range.

The following expressions for elevated-temperature property ratios, which were derived by fitting curves to short-time data, have proven useful in analytical modeling (R. L. Brockenbrough, "Theoretical Stresses and Strains from Heat Curving," *Journal of the Structural Division, American Society of Civil Engineers,* Vol. 96, No. ST7, 1970):

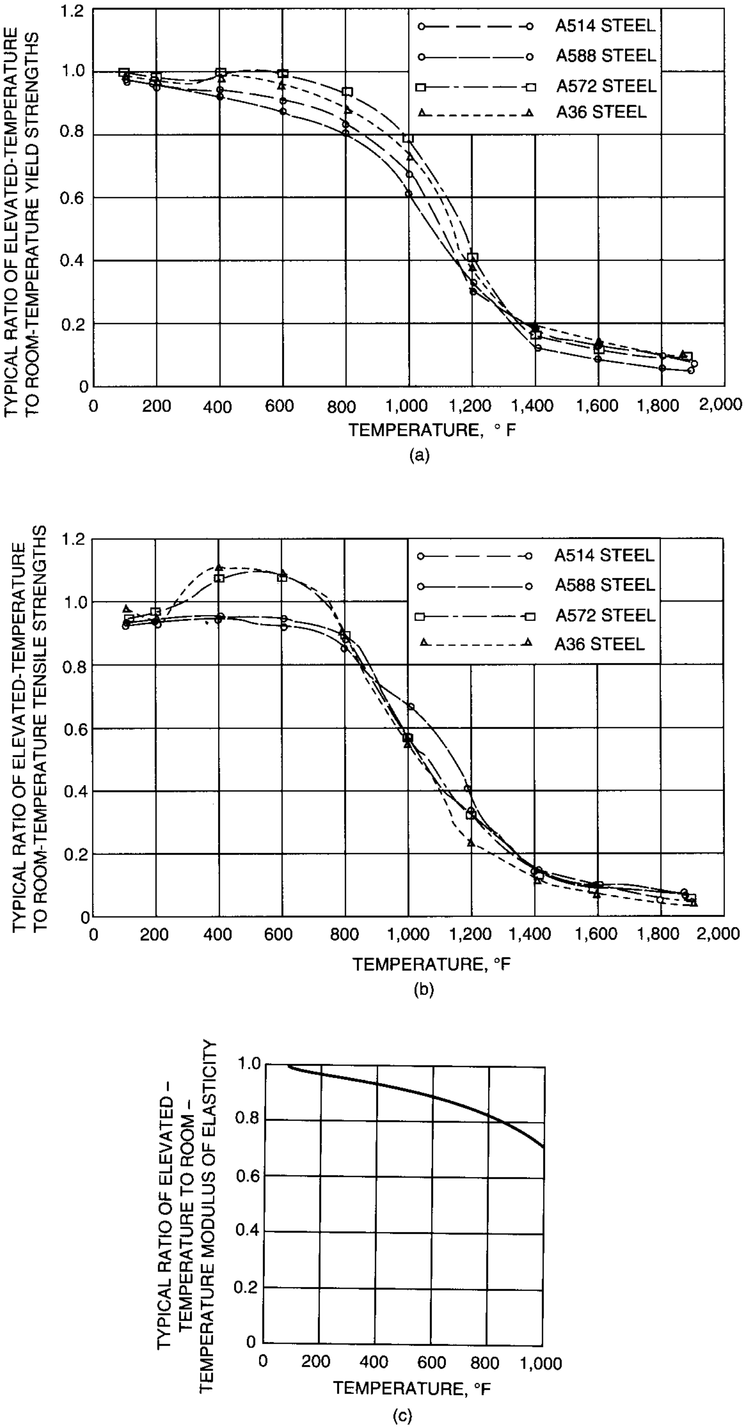

FIGURE 1.9 Effect of temperature on (*a*) yield strengths, (*b*) tensile strengths, and (*c*) modulus of elasticity of structural steels. (*From R. L. Brockenbrough and B. G. Johnston, USS Steel Design Manual, R. L. Brockenbrough & Associates, Inc., Pittsburgh, Pa., with permission.*)

$$F_y/F'_y = 1 - \frac{T - 100}{5833} \qquad 100°F < T < 800°F \tag{1.9}$$

$$F_y/F'_y = (-720{,}000 + 4200 - 2.75T^2)10^{-6} \qquad 800°F < T < 1200°F \tag{1.10}$$

$$E/E' = 1 - \frac{T - 100}{5000} \qquad 100°F < T < 700°F \tag{1.11}$$

$$E/E' = (500{,}000 + 1333T - 1.111T^2)10^{-6} \qquad 700°F < T < 1200°F \tag{1.12}$$

$$\alpha = (6.1 + 0.0019T)10^{-6} \qquad 100°F < T < 1200°F \tag{1.13}$$

In these equations F_y/F'_y and E/E' are the ratios of elevated-temperature to room-temperature yield strength and modulus of elasticity, respectively, α is the coefficient of thermal expansion per degree Fahrenheit, and T is the temperature in degrees Fahrenheit.

Ductility of structural steels, as indicated by elongation and reduction-of-area values, decreases with increasing temperature until a minimum value is reached. Thereafter, ductility increases to a value much greater than that at room temperature. The exact effect depends on the type and thickness of steel. The initial decrease in ductility is caused by strain aging and is most pronounced in the temperature range of 300 to 700°F. Strain aging also accounts for the increase in tensile strength in this temperature range shown for two of the steels in Fig. 1.9*b*.

Under long-time loadings at elevated temperatures, the effects of creep must be considered. When a load is applied to a specimen at an elevated temperature, the specimen deforms rapidly at first but then continues to deform, or creep, at a much slower rate. A schematic creep curve for a steel subjected to a constant tensile load and at a constant elevated temperature is shown in Fig. 1.10. The initial elongation occurs almost instantaneously and is followed by three stages. In stage 1 elongation increases at a decreasing rate. In stage 2, elongation increases at a nearly constant rate. And in stage 3, elongation increases at an increasing rate. The failure, or creep-rupture, load is less than the load that would cause failure at that temperature in a short-time loading test.

Table 1.9 indicates typical creep and rupture data for a carbon steel, an HSLA steel, and a constructional alloy steel. The table gives the stress that will cause a given amount of creep in a given time at a particular temperature.

For special elevated-temperature applications in which structural steels do not provide adequate properties, special alloy and stainless steels with excellent high-temperature properties are available.

1.13 FATIGUE

A structural member subjected to cyclic loadings may eventually fail through initiation and propagation of cracks. This phenomenon is called **fatigue** and can occur at stress levels considerably below the yield stress.

Extensive research programs conducted to determine the fatigue strength of structural members and connections have provided information on the factors affecting this property. These programs included studies of large-scale girder specimens with flange-to-web fillet welds, flange cover plates, stiffeners, and other attachments. The studies showed that the **stress range** (algebraic difference between maximum and minimum stress) and **notch severity** of details are the most important factors. Yield point of the steel had little effect. The knowledge developed from these programs has been incorporated into specifications of the American Institute of Steel Construction, American Association of State Highway and Transportation Officials, and the American Railway Engineering and Maintenance-of-Way Association, which offer detailed provisions for fatigue design.

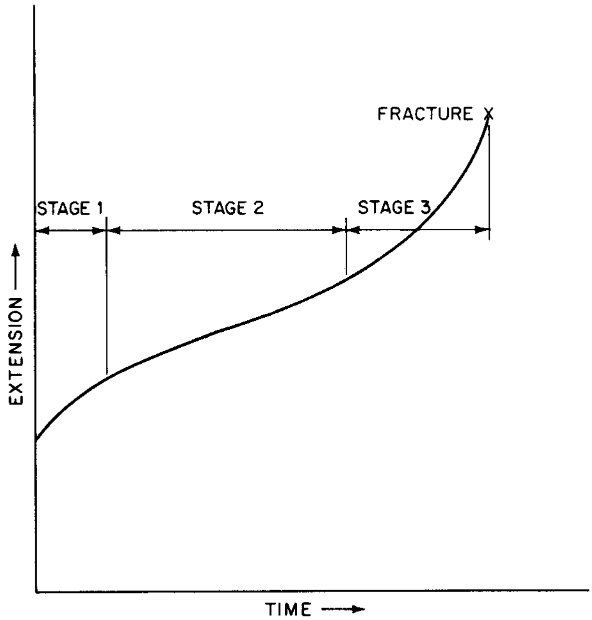

FIGURE 1.10 Creep curve for structural steel in tension (schematic). (*From R. L. Brockenbrough and B. G. Johnston, USS Steel Design Manual, R. L. Brockenbrough & Associates, Inc., Pittsburgh, Pa., with permission.*)

1.14 BRITTLE FRACTURE

Under sufficiently adverse combinations of tensile stress, temperature, loading rate, geometric discontinuity (notch), and restraint, a steel member may experience a brittle fracture. All these factors need not be present. In general, a **brittle fracture** is a failure that occurs by cleavage with little indication of plastic deformation. In contrast, a **ductile fracture** occurs mainly by shear, usually preceded by considerable plastic deformation.

Design against brittle fracture requires selection of the proper grade of steel for the application and avoiding notchlike defects in both design and fabrication. An awareness of the phenomenon is important so that steps can be taken to minimize the possibility of this undesirable, usually catastrophic failure mode.

An empirical approach and an analytical approach directed toward selection and evaluation of steels to resist brittle fracture are outlined below. These methods are actually complementary and are frequently used together in evaluating material and fabrication requirements.

Charpy V-Notch Test. Many tests have been developed to rate steels on their relative resistance to brittle fracture. One of the most commonly used tests is the Charpy V-notch test, which specifically evaluates notch toughness, that is, the resistance to fracture in the presence of a notch. In this test, a small square bar with a specified-size V-shaped notch at its midlength (type A impact-test specimen of ASTM A370) is simply supported at its ends as a beam and fractured by a blow from a swinging pendulum. The amount of energy required to fracture the specimen or the appearance of the fracture surface is determined over a range of temperatures. The appearance of the fracture surface is usually expressed as the percentage of the surface that appears to have fractured by shear.

TABLE 1.9 Typical Creep Rates and Rupture Stresses for Structural Steels at Various Temperatures

Test temperature, °F	Stress, ksi, for creep rate of		Stress, ksi for rupture in		
	0.0001% per hr*	0.00001% per hr†	1000 hours	10,000 hours	100,000 hours
			A36 steel		
800	21.4	13.8	38.0	24.8	16.0
900	9.9	6.0	18.5	12.4	8.2
1000	4.6	2.6	9.5	6.3	4.2
			A588 grade A steel†		
800	34.6	29.2	44.1	35.7	28.9
900	20.3	16.3	28.6	22.2	17.3
1000	11.4	8.6	17.1	12.0	8.3
1200	1.7	1.0	3.8	2.0	1.0
			A514 grade F steel†		
700	—	—	101.0	99.0	97.0
800	81.0	74.0	86.0	81.0	77.0

*Equivalent to 1% in 10,000 hours.
†Equivalent to 1% in 100,000 hours.
‡Not recommended for use where temperatures exceed 800°F.

A **shear fracture** is indicated by a dull or fibrous appearance. A shiny or crystalline appearance is associated with a **cleavage fracture.**

The data obtained from a Charpy test are used to plot curves, such as those in Fig. 1.11, of energy or percentage of shear fracture as a function of temperature. The temperature near the bottom of the energy-temperature curve, at which a selected low value of energy is absorbed, often 15 ft · lb, is called the **ductility transition temperature** or the **15-ft · lb**

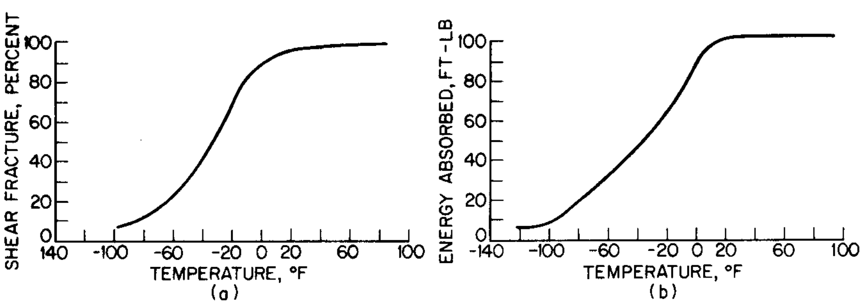

FIGURE 1.11 Transition curves from Charpy-V notch impact tests. (*a*) Variation of percent shear fracture with temperature. (*b*) Variation of absorbed energy with temperature.

transition temperature. The temperature at which the percentage of shear fracture decreases to 50% is often called the **fracture-appearance transition temperature.** These transition temperatures serve as a rating of the resistance of different steels to brittle fracture. The lower the transition temperature, the greater is the notch toughness.

Of the steels in Table 1.1, A36 steel generally has about the highest transition temperature. Since this steel has an excellent service record in a variety of structural applications, it appears likely that any of the structural steels, when designed and fabricated in an appropriate manner, could be used for similar applications with little likelihood of brittle fracture. Nevertheless, it is important to avoid unusual temperature, notch, and stress conditions to minimize susceptibility to brittle fracture.

In applications where notch toughness is considered important, the minimum Charpy V-notch value and test temperature should be specified, because there may be considerable variation in toughness within any given product designation unless specifically produced to minimum requirements. The test temperature may be specified higher than the lowest operating temperature to compensate for a lower rate of loading in the anticipated application. (See Art. 1.1.5.)

It should be noted that as the thickness of members increases, the inherent restraint increases and tends to inhibit ductile behavior. Thus special precautions or greater toughness, or both, is required for tension or flexural members comprised of thick material. (See Art. 1.17.)

Fracture-Mechanics Analysis. Fracture mechanics offers a more direct approach for prediction of crack propagation. For this analysis, it is assumed that a **crack,** which may be defined as a flat, internal defect, is always present in a stressed body. By linear-elastic stress analysis and laboratory tests on a precracked specimen, the defect size is related to the applied stress that will cause crack propagation and brittle fracture, as outlined below.

Near the tip of a crack, the stress component f perpendicular to the plane of the crack (Fig. 1.12a) can be expressed as

$$f = \frac{K_I}{\sqrt{2\pi r}} \tag{1.14}$$

where r is distance from tip of crack and K_I is a stress-intensity factor related to geometry

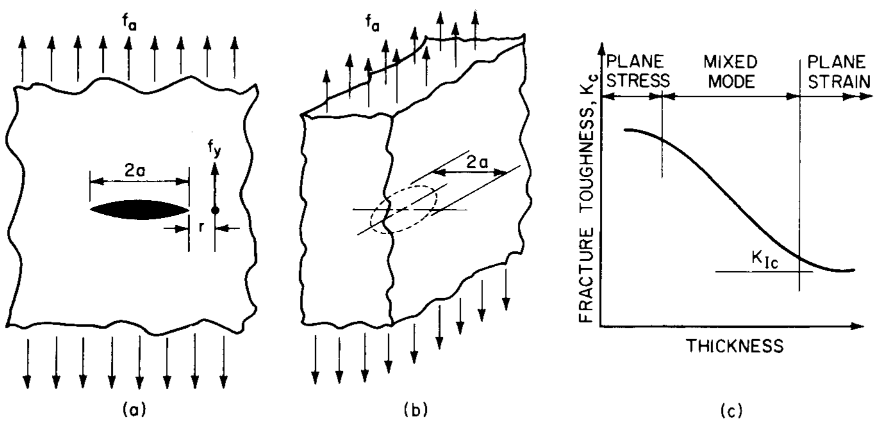

FIGURE 1.12 Fracture mechanics analysis for brittle fracture. (a) Sharp crack in a stressed infinite plate. (b) Disk-shaped crack in an infinite body. (c) Relation of fracture toughness to thickness.

of crack and to applied loading. The factor K_I can be determined from elastic theory for given crack geometries and loading conditions. For example, for a through-thickness crack of length $2a$ in an infinite plate under uniform stress (Fig. 1.12*a*),

$$K_I = f_a \sqrt{\pi a} \tag{1.15}$$

where f_a is the nominal applied stress. For a disk-shaped crack of diameter $2a$ embedded in an infinite body (Fig. 1.12*b*), the relationship is

$$K_I = 2 f_a \sqrt{\frac{a}{\pi}} \tag{1.16}$$

If a specimen with a crack of known geometry is loaded until the crack propagates rapidly and causes failure, the value of K_I at that stress level can be calculated from the derived expression. This value is termed the **fracture toughness** K_c.

A precracked tension or bend-type specimen is usually used for such tests. As the thickness of the specimen increases and the stress condition changes from plane stress to plane strain, the fracture toughness decreases to a minimum value, as illustrated in Fig. 1.12*c*. This value of plane-strain fracture toughness designated K_{Ic}, may be regarded as a fundamental material property.

Thus, if K_{Ic} is substituted for K_I, for example, in Eq. (1.15) or (1.16) a numerical relationship is obtained between the crack geometry and the applied stress that will cause fracture. With this relationship established, brittle fracture may be avoided by determining the maximum-size crack present in the body and maintaining the applied stress below the corresponding level. The tests must be conducted at or correlated with temperatures and strain rates appropriate for the application, because fracture toughness decreases with temperature and loading rate. Correlations have been made to enable fracture toughness values to be estimated from the results of Charpy V-notch tests.

Fracture-mechanics analysis has proven quite useful, particularly in critical applications. Fracture-control plans can be established with suitable inspection intervals to ensure that imperfections, such as fatigue cracks do not grow to critical size.

(J. M. Barsom and S. T. Rolfe, *Fracture and Fatigue Control in Structures; Applications of Fracture Mechanics,* Prentice-Hall, Inc. Englewood Cliffs, N.J.)

1.15 RESIDUAL STRESSES

Stresses that remain in structural members after rolling or fabrication are known as **residual stresses.** The magnitude of the stresses is usually determined by removing longitudinal sections and measuring the strain that results. Only the longitudinal stresses are usually measured. To meet equilibrium conditions, the axial force and moment obtained by integrating these residual stresses over any cross section of the member must be zero.

In a hot-rolled structural shape, the residual stresses result from unequal cooling rates after rolling. For example, in a wide-flange beam, the center of the flange cools more slowly and develops tensile residual stresses that are balanced by compressive stresses elsewhere on the cross section (Fig. 1.13*a*). In a welded member, tensile residual stresses develop near the weld and compressive stresses elsewhere provide equilibrium, as shown for the welded box section in Fig. 1.13*b*.

For plates with rolled edges (UM plates), the plate edges have compressive residual stresses (Fig. 1.13*c*). However, the edges of flame-cut plates have tensile residual stresses (Fig. 1.13*d*). In a welded I-shaped member, the stress condition in the edges of flanges before welding is reflected in the final residual stresses (Fig. 1.13*e*). Although not shown in Fig. 1.13, the residual stresses at the edges of sheared-edge plates vary through the plate

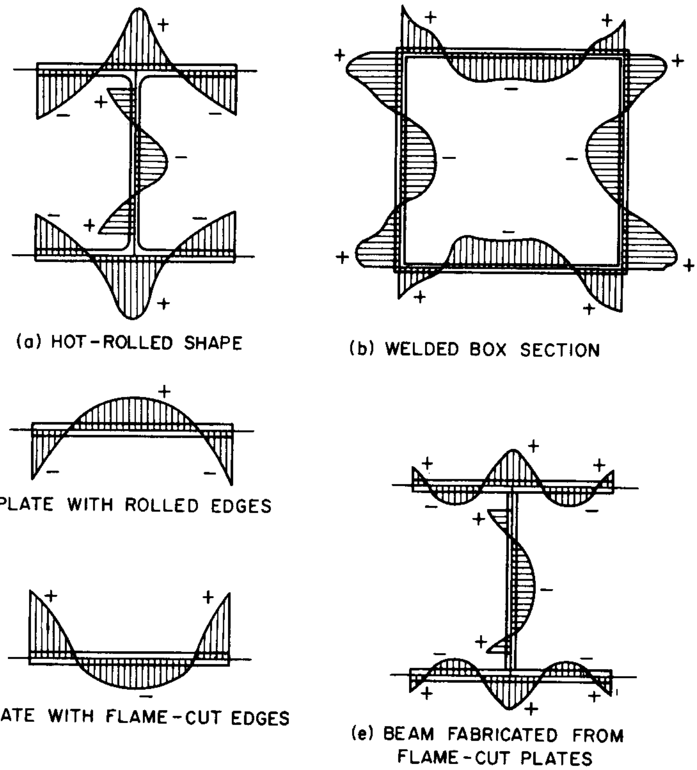

FIGURE 1.13 Typical residual-stress distributions (+ indicates tension and − compression).

thickness. Tensile stresses are present on one surface and compressive stresses on the opposite surface.

The residual-stress distributions mentioned above are usually relatively constant along the length of the member. However, residual stresses also may occur at particular locations in a member, because of localized plastic flow from fabrication operations, such as cold straightening or heat straightening.

When loads are applied to structural members, the presence of residual stresses usually causes some premature inelastic action; that is, yielding occurs in localized portions before the nominal stress reaches the yield point. Because of the ductility of steel, the effect on strength of tension members is not usually significant, but excessive tensile residual stresses, in combination with other conditions, can cause fracture. In compression members, residual stresses decrease the buckling load from that of an ideal or perfect member. However, current design criteria in general use for compression members account for the influence of residual stress.

In bending members that have residual stresses, a small inelastic deflection of insignificant magnitude may occur with the first application of load. However, under subsequent loads of the same magnitude, the behavior is elastic. Furthermore, in "compact" bending members, the presence of residual stresses has no effect on the ultimate moment (plastic moment). Consequently, in the design of statically loaded members, it is not usually necessary to consider residual stresses.

1.16 LAMELLAR TEARING

In a structural steel member subjected to tension, elongation and reduction of area in sections normal to the stress are usually much lower in the through-thickness direction than in the planar direction. This inherent directionality is of small consequence in many applications, but it does become important in design and fabrication of structures with highly restrained joints because of the possibility of **lamellar tearing.** This is a cracking phenomenon that starts underneath the surface of steel plates as a result of excessive through-thickness strain, usually associated with shrinkage of weld metal in highly restrained joints. The tear has a steplike appearance consisting of a series of terraces parallel to the surface. The cracking may remain completely below the surface or may emerge at the edges of plates or shapes or at weld toes.

Careful selection of weld details, filler metal, and welding procedure can restrict lamellar tearing in heavy welded constructions, particularly in joints with thick plates and heavy structural shapes. Also, when required, structural steels can be produced by special processes, generally with low sulfur content and inclusion control, to enhance through-thickness ductility.

The most widely accepted method of measuring the susceptibility of a material to lamellar tearing is the tension test on a round specimen, in which is observed the reduction in area of a section oriented perpendicular to the rolled surface. The reduction required for a given application depends on the specific details involved. The specifications to which a particular steel can be produced are subject to negotiations with steel producers.

(R. L. Brockenbrough, Chap. 1.2 in *Constructional Steel Design—An International Guide,* R. Bjorhovde et al., eds., Elsevier Science Publishers, Ltd., New York.)

1.17 WELDED SPLICES IN HEAVY SECTIONS

Shrinkage during solidification of large welds in structural steel members causes, in adjacent restrained metal, strains that can exceed the yield-point strain. In thick material, triaxial stresses may develop because there is restraint in the thickness direction as well as in planar directions. Such conditions inhibit the ability of a steel to act in a ductile manner and increase the possibility of brittle fracture. Therefore, for members subject to primary tensile stresses due to axial tension or flexure in buildings, the American Institute of Steel Construction (AISC) specifications for structural steel buildings impose special requirements for welded splicing of either group 4 or group 5 rolled shapes or of shapes built up by welding plates more than 2 in thick. The specifications include requirements for notch toughness, removal of weld tabs and backing bars (welds ground smooth), generous-sized weld-access holes, preheating for thermal cutting, and grinding and inspecting cut edges. Even for primary compression members, the same precautions should be taken for sizing weld access holes, preheating, grinding, and inspection.

Most heavy wide-flange shapes and tees cut from these shapes have regions where the steel has low toughness, particularly at flange-web intersections. These low-toughness regions occur because of the slower cooling there and, because of the geometry, the lower rolling pressure applied there during production. Hence, to ensure ductility and avoid brittle failure, bolted splices should be considered as an alternative to welding.

(''AISC Specification for Structural Steel Buildings—Allowable Stress Design and Plastic Design'' and ''Load and Resistance Factor Design Specification for Structural Steel Buildings,'' American Institute of Steel Construction; R. L. Brockenbrough, Sec. 9, in *Standard Handbook for Civil Engineers,* 4th ed., McGraw-Hill, Inc., New York.)

1.18 k-AREA CRACKING

Wide flange sections are typically straightened as part of the mill production process. Often a rotary straightening process is used, although some heavier members may be straightened in a gag press. Some reports in recent years have indicated a potential for crack initiation at or near connections in the "*k*" area of wide flange sections that have been rotary straightened. The *k* area is the region extending from approximately the mid-point of the web-to-flange fillet, into the web for a distance approximately 1 to 1½ in beyond the point of tangency. Apparently, in some cases, this limited region had a reduced notch toughness due to cold working and strain hardening. Most of the incidents reported occurred at highly restrained joints with welds in the *k* area. However, the number of examples reported has been limited and these have occurred during construction or laboratory tests, with no evidence of difficulties with steel members in service.

Research sponsored by AISC is underway to define the extent of the problem and make appropriate recommendations. Until further information is available, AISC has issued the following recommendations concerning fabrication and design practices for rolled wide flange shapes:

- Welds should be stopped short of the "*k*" area for transverse stiffeners (continuity plates).
- For continuity plates, fillet welds and/or partial joint penetration welds, proportioned to transfer the calculated stresses to the column web, should be considered instead of complete joint penetration welds. Weld volume should be minimized.
- Residual stresses in highly restrained joints may be decreased by increased preheat and proper weld sequencing.
- Magnetic particle or dye penetrant inspection should be considered for weld areas in or near the *k* area of highly restrained connections after the final welding has completely cooled.
- When possible, eliminate the need for column web doubler plates by increasing column size.

Good fabrication and quality control practices, such as inspection for cracks and gouges at flame-cut access holes or copes, should continue to be followed and any defects repaired and ground smooth. All structural wide flange members for normal service use in building construction should continue to be designed per AISC Specifications and the material furnished per ASTM standards."

(AISC Advisory Statement, *Modern Steel Construction,* February 1997.)

1.19 VARIATIONS IN MECHANICAL PROPERTIES

Tensile properties of structural steel may vary from specified minimum values. Product specifications generally require that properties of the material "as represented by the test specimen" meet certain values. With some exceptions, ASTM specifications dictate a test frequency for structural-grade steels of only two tests per heat (in each strength level produced, if applicable) and more frequent testing for pressure-vessel grades. If the heats are very large, the test specimens qualify a considerable amount of product. As a result, there is a possibility that properties at locations other than those from which the specimens were taken will be different from those specified.

For plates, a test specimen is required by ASTM A6 to be taken from a corner. If the plates are wider than 24 in, the longitudinal axis of the specimen should be oriented transversely to the final direction in which the plates were rolled. For other products, however, the longitudinal axis of the specimen should be parallel to the final direction of rolling.

For structural shapes with a flange width of 6 in or more, test specimens should be selected from a point in the flange as near as practicable to ⅔ the distance from the flange centerline to the flange toe. Prior to 1997–1998, the specimens were taken from the web.

An extensive study commissioned by the American Iron and Steel Institute (AISI) compared yield points at various sample locations with the official product test. The studies indicated that the average difference at the check locations was −0.7 ksi. For the top and bottom flanges, at either end of beams, the average difference at check locations was −2.6 ksi.

Although the test value at a given location may be less than that obtained in the official test, the difference is offset to the extent that the value from the official test exceeds the specified minimum value. For example, a statistical study made to develop criteria for load and resistance factor design showed that the mean yield points exceeded the specified minimum yield point F_y (specimen located in web) as indicated below and with the indicated coefficient of variation (COV).

Flanges of rolled shapes	$1.05F_y$, COV = 0.10
Webs of rolled shapes	$1.10F_y$, COV = 0.11
Plates	$1.10F_y$, COV = 0.11

Also, these values incorporate an adjustment to the lower ''static'' yield points.

For similar reasons, the notch toughness can be expected to vary throughout a product.

(R. L. Brockenbrough, Chap. 1.2, in *Constructional Steel Design—An International Guide,* R. Bjorhovde, ed., Elsevier Science Publishers, Ltd., New York.)

1.20 CHANGES IN CARBON STEELS ON HEATING AND COOLING*

As pointed out in Art. 1.12, heating changes the tensile properties of steels. Actually, heating changes many steel properties. Often, the primary reason for such changes is a change in structure brought about by heat. Some of these structural changes can be explained with the aid of an iron-carbon equilibrium diagram (Fig. 1.14).

The diagram maps out the constituents of carbon steels at various temperatures as carbon content ranges from 0 to 5%. Other elements are assumed to be present only as impurities, in negligible amounts.

If a steel with less than 2% carbon is very slowly cooled from the liquid state, a solid solution of carbon in gamma iron will result. This is called **austenite.** (Gamma iron is a pure iron whose crystalline structure is face-centered cubic.)

If the carbon content is about 0.8%, the carbon remains in solution as the austenite slowly cools, until the A_1 temperature (1340°F) is reached. Below this temperature, the austenite transforms to the eutectoid **pearlite.** This is a mixture of ferrite and **cementite** (iron carbide, Fe_3C). Pearlite, under a microscope, has a characteristic platelike, or lamellar, structure with an iridescent appearance, from which it derives its name.

If the carbon content is less than 0.8%, as is the case with structural steels, cooling austenite below the A_3 temperature line causes transformation of some of the austenite to **ferrite.** (This is a pure iron, also called **alpha iron,** whose crystalline structure is body-centered cubic.) Still further cooling to below the A_1 line causes the remaining austenite to

*Articles 1.20 through 1.28 adapted from previous edition written by Frederick S. Merritt, Consulting Engineer, West Palm Beach, Florida.

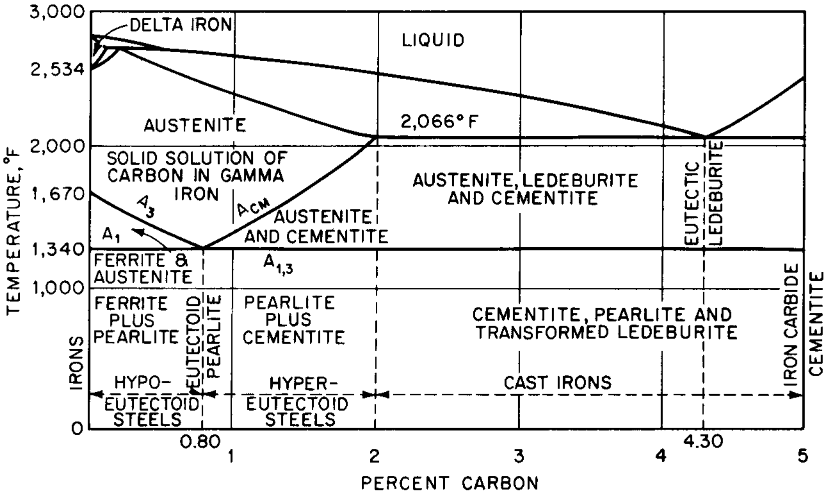

FIGURE 1.14 Iron-carbon equilibrium diagram.

transform to pearlite. Thus, as indicated in Fig. 1.14, low-carbon steels are **hypoeutectoid steels,** mixtures of ferrite and pearlite.

Ferrite is very ductile but has low tensile strength. Hence carbon steels get their high strengths from the pearlite present or, more specifically, from the cementite in the pearlite.

The iron-carbon equilibrium diagram shows only the constituents produced by slow cooling. At high cooling rates, however, equilibrium cannot be maintained. Transformation temperatures are lowered, and steels with microstructures other than pearlitic may result. Properties of such steels differ from those of the pearlitic steels. Heat treatments of steels are based on these temperature effects.

If a low-carbon austenite is rapidly cooled below about 1300°F, the austenite will transform at constant temperature into steels with one of four general classes of microstructure:

Pearlite, or lamellar, microstructure results from transformations in the range 1300 to 1000°F. The lower the temperature, the closer is the spacing of the platelike elements. As the spacing becomes smaller, the harder and tougher the steels become. Steels such as A36, A572, and A588 have a mixture of a soft ferrite matrix and a hard pearlite.

Bainite forms in transformations below about 1000°F and above about 450°F. It has an acicular, or needlelike, microstructure. At the higher temperatures, bainite may be softer than the pearlitic steels. However, as the transformation temperature is decreased, hardness and toughness increase.

Martensite starts to form at a temperature below about 500°F, called the M_s temperature. The transformation differs from those for pearlitic and bainitic steels in that it is not time-dependent. Martensite occurs almost instantly during rapid cooling, and the percentage of austenite transformed to martensite depends only on the temperature to which the steel is cooled. For complete conversion to martensite, cooling must extend below the M_f temperature, which may be 200°F or less. Like bainite, martensite has an acicular microstructure, but martensite is harder and more brittle than pearlitic and bainitic steels. Its hardness varies with carbon content and to some extent with cooling rate. For some applications, such as those where wear resistance is important, the high hardness of martensite is desirable, despite brittleness. Generally, however, martensite is used to obtain tempered martensite, which has superior properties.

Tempered martensite is formed when martensite is reheated to a subcritical temperature after quenching. The tempering precipitates and coagulates carbides. Hence the microstructure consists of carbide particles, often spheroidal in shape, dispersed in a ferrite matrix. The result is a loss in hardness but a considerable improvement in ductility and toughness. The heat-treated carbon and HSLA steels and quenched and tempered constructional steels discussed in Art. 1.1 are low-carbon martensitic steels.

(Z. D. Jastrzebski, *Nature and Properties of Engineering Materials,* John Wiley & Sons, Inc., New York.)

1.21 EFFECTS OF GRAIN SIZE

As indicated in Fig. 1.14, when a low-carbon steel is heated above the A_1 temperature line, austenite, a solid solution of carbon in gamma iron, begins to appear in the ferrite matrix. Each island of austenite grows until it intersects its neighbor. With further increase in temperature, these grains grow larger. The final grain size depends on the temperature above the A_3 line to which the metal is heated. When the steel cools, the relative coarseness of the grains passes to the ferrite-plus-pearlite phase.

At rolling and forging temperatures, therefore, many steels grow coarse grains. Hot working, however, refines the grain size. The temperature at the final stage of the hot-working process determines the final grain size. When the finishing temperature is relatively high, the grains may be rather coarse when the steel is air-cooled. In that case, the grain size can be reduced if the steel is normalized (reheated to just above the A_3 line and again air-cooled). (See Art. 1.22.)

Fine grains improve many properties of steels. Other factors being the same, steels with finer grain size have better notch toughness because of lower transition temperatures (see Art. 1.14) than coarser-grained steels. Also, decreasing grain size improves bendability and ductility. Furthermore fine grain size in quenched and tempered steel improves yield strength. And there is less distortion, less quench cracking, and lower internal stress in heat-treated products.

On the other hand, for some applications, coarse-grained steels are desirable. They permit deeper hardening. If the steels should be used in elevated-temperature service, they offer higher load-carrying capacity and higher creep strength than fine-grained steels.

Austenitic-grain growth may be inhibited by carbides that dissolve slowly or remain undissolved in the austenite or by a suitable dispersion of nonmetallic inclusions. Steels produced this way are called **fine-grained.** Steels not made with grain-growth inhibitors are called **coarse-grained.**

When heated above the critical temperature, 1340°F, grains in coarse-grained steels grow gradually. The grains in fine-grained steels grow only slightly, if at all, until a certain temperature, the coarsening temperature, is reached. Above this, abrupt coarsening occurs. The resulting grain size may be larger than that of coarse-grained steel at the same temperature. Note further that either fine-grained or coarse-grained steels can be heat-treated to be either fine-grained or coarse-grained (see Art. 1.22).

The usual method of making fine-grained steels involves controlled aluminum deoxidation (see also Art. 1.24). The inhibiting agent in such steels may be a submicroscopic dispersion of aluminum nitride or aluminum oxide.

(W. T. Lankford, Jr., ed., *The Making, Shaping and Treating of Steel,* Association of Iron and Steel Engineers, Pittsburgh, Pa.)

1.22 ANNEALING AND NORMALIZING

Structural steels may be annealed to relieve stresses induced by cold or hot working. Sometimes, also, annealing is used to soften metal to improve its formability or machinability.

Annealing involves austenitizing the steel by heating it above the A_3 temperature line in Fig. 1.14, then cooling it slowly, usually in a furnace. This treatment improves ductility but decreases tensile strength and yield point. As a result, further heat treatment may be necessary to improve these properties.

Structural steels may be normalized to refine grain size. As pointed out in Art. 1.21, grain size depends on the finishing temperature in hot rolling.

Normalizing consists of heating the steel above the A_3 temperature line, then cooling the metal in still air. Thus the rate of cooling is more rapid than in annealing. Usual practice is to normalize from 100 to 150°F above the critical temperature. Higher temperatures coarsen the grains.

Normalizing tends to improve notch toughness by lowering ductility and fracture transition temperatures. Thick plates benefit more from this treatment than thin plates. Requiring fewer roller passes, thick plates have a higher finishing temperature and cool slower than thin plates, thus have a more adverse grain structure. Hence the improvement from normalizing is greater for thick plates.

1.23 EFFECTS OF CHEMISTRY ON STEEL PROPERTIES

Chemical composition determines many characteristics of steels important in construction applications. Some of the chemicals present in commercial steels are a consequence of the steelmaking process. Other chemicals may be added deliberately by the producers to achieve specific objectives. Specifications therefore usually require producers to report the chemical composition of the steels.

During the pouring of a heat of steel, producers take samples of the molten steel for chemical analysis. These heat analyses are usually supplemented by product analyses taken from drillings or millings of blooms, billets, or finished products. ASTM specifications contain maximum and minimum limits on chemicals reported in the heat and product analyses, which may differ slightly.

Principal effects of the elements more commonly found in carbon and low-alloy steels are discussed below. Bear in mind, however, that the effects of two or more of these chemicals when used in combination may differ from those when each alone is present. Note also that variations in chemical composition to obtain specific combinations of properties in a steel usually increase cost, because it becomes more expensive to make, roll, and fabricate.

Carbon is the principal strengthening element in carbon and low-alloy steels. In general, each 0.01% increase in carbon content increases the yield point about 0.5 ksi. This, however, is accompanied by increase in hardness and reduction in ductility, notch toughness, and weldability, raising of the transition temperatures, and greater susceptibility to aging. Hence limits on carbon content of structural steels are desirable. Generally, the maximum permitted in structural steels is 0.30% or less, depending on the other chemicals present and the weldability and notch toughness desired.

Aluminum, when added to silicon-killed steel, lowers the transition temperature and increases notch toughness. If sufficient aluminum is used, up to about 0.20%, it reduces the transition temperature even when silicon is not present. However, the larger additions of aluminum make it difficult to obtain desired finishes on rolled plate. Drastic deoxidation of molten steels with aluminum or aluminum and titanium, in either the steelmaking furnace or the ladle, can prevent the spontaneous increase in hardness at room temperature called **aging.** Also, aluminum restricts grain growth during heat treatment and promotes surface hardness by nitriding.

Boron in small quantities increases hardenability of steels. It is used for this purpose in quenched and tempered low-carbon constructional alloy steels. However, more than 0.0005 to 0.004% boron produces no further increase in hardenability. Also, a trace of boron increases strength of low-carbon, plain molybdenum (0.40%) steel.

Chromium improves strength, hardenability, abrasion resistance, and resistance to atmospheric corrosion. However, it reduces weldability. With small amounts of chromium, low-alloy steels have higher creep strength than carbon steels and are used where higher strength is needed for elevated-temperature service. Also chromium is an important constituent of stainless steels.

Columbium in very small amounts produces relatively larger increases in yield point but smaller increases in tensile strength of carbon steel. However, the notch toughness of thick sections is appreciably reduced.

Copper in amounts up to about 0.35% is very effective in improving the resistance of carbon steels to atmospheric corrosion. Improvement continues with increases in copper content up to about 1% but not so rapidly. Copper increases strength, with a proportionate increase in fatigue limit. Copper also increases hardenability, with only a slight decrease in ductility and little effect on notch toughness and weldability. However, steels with more than 0.60% copper are susceptible to precipitation hardening. And steels with more than about 0.5% copper often experience hot shortness during hot working, and surface cracks or roughness develop. Addition of nickel in an amount equal to about half the copper content is effective in maintaining surface quality.

Hydrogen, which may be absorbed during steelmaking, embrittles steels. Ductility will improve with aging at room temperature as the hydrogen diffuses out of the steel, faster from thin sections than from thick. When hydrogen content exceeds 0.0005%, flaking, internal cracks or bursts, may occur when the steel cools after rolling, especially in thick sections. In carbon steels, flaking may be prevented by slow cooling after rolling, to permit the hydrogen to diffuse out of the steel.

Manganese increases strength, hardenability, fatigue limit, notch toughness, and corrosion resistance. It lowers the ductility and fracture transition temperatures. It hinders aging. Also, it counteracts hot shortness due to sulfur. For this last purpose, the manganese content should be three to eight times the sulfur content, depending on the type of steel. However, manganese reduces weldability.

Molybdenum increases yield strength, hardenability, abrasion resistance, and corrosion resistance. It also improves weldability. However, it has an adverse effect on toughness and transition temperature. With small amounts of molybdenum, low-alloy steels have higher creep strength than carbon steels and are used where higher strength is needed for elevated-temperature service.

Nickel increases strength, hardenability, notch toughness, and corrosion resistance. It is an important constituent of stainless steels. It lowers the ductility and fracture transition temperatures, and it reduces weldability.

Nitrogen increases strength, but it may cause aging. It also raises the ductility and fracture transition temperatures.

Oxygen, like nitrogen, may be a cause of aging. Also, oxygen decreases ductility and notch toughness.

Phosphorus increases strength, fatigue limit, and hardenability, but it decreases ductility and weldability and raises the ductility transition temperature. Additions of aluminum, however, improve the notch toughness of phosphorus-bearing steels. Phosphorus improves the corrosion resistance of steel and works very effectively together with small amounts of copper toward this result.

Silicon increases strength, notch toughness, and hardenability. It lowers the ductility transition temperature, but it also reduces weldability. Silicon often is used as a deoxidizer in steelmaking (see Art. 1.24).

Sulfur, which enters during the steelmaking process, can cause hot shortness. This results from iron sulfide inclusions, which soften and may rupture when heated. Also, the inclusions may lead to brittle failure by providing stress raisers from which fractures can initiate. And high sulfur contents may cause porosity and hot cracking in welding unless special precautions are taken. Addition of manganese, however, can counteract hot shortness. It forms manganese sulfide, which is more refractory than iron sulfide. Nevertheless, it usually is desirable to keep sulfur content below 0.05%.

Titanium increases creep and rupture strength and abrasion resistance. It plays an important role in preventing aging. It sometimes is used as a deoxidizer in steelmaking (see Art. 1.24) and grain-growth inhibitor (see Art. 1.21).

Tungsten increases creep and rupture strength, hardenability and abrasion resistance. It is used in steels for elevated-temperature service.

Vanadium, in amounts up to about 0.12%, increases rupture and creep strength without impairing weldability or notch toughness. It also increases hardenability and abrasion resistance. Vanadium sometimes is used as a deoxidizer in steelmaking (see Art. 1.24) and grain-growth inhibitor (see Art. 1.21).

In practice, carbon content is limited so as not to impair ductility, notch toughness, and weldability. To obtain high strength, therefore, resort is had to other strengthening agents that improve these desirable properties or at least do not impair them as much as carbon. Often, the better these properties are required to be at high strengths, the more costly the steels are likely to be.

Attempts have been made to relate chemical composition to weldability by expressing the relative influence of chemical content in terms of **carbon equivalent.** One widely used formula, which is a supplementary requirement in ASTM A6 for structural steels, is

$$C_{eq} = \mathrm{C} + \frac{\mathrm{Mn}}{6} + \frac{(\mathrm{Cr} + \mathrm{Mo} + \mathrm{V})}{5} + \frac{(\mathrm{Ni} + \mathrm{Cu})}{15} \tag{1.17}$$

where C = carbon content, %
Mn = manganese content, %
Cr = chromium content, %
Mo = molybdenum, %
V = vanadium, %
Ni = nickel content, %
Cu = copper, %

Carbon equivalent is related to the maximum rate at which a weld and adjacent plate may be cooled after welding, without underbead cracking occurring. The higher the carbon equivalent, the lower will be the allowable cooling rate. Also, use of low-hydrogen welding electrodes and preheating becomes more important with increasing carbon equivalent. (*Structural Welding Code—Steel,* American Welding Society, Miami, Fla.)

Though carbon provides high strength in steels economically, it is not a necessary ingredient. Very high strength steels are available that contain so little carbon that they are considered carbon-free.

Maraging steels, carbon-free iron-nickel martensites, develop yield strengths from 150 to 300 ksi, depending on alloying composition. As pointed out in Art. 1.20, iron-carbon martensite is hard and brittle after quenching and becomes softer and more ductile when tempered. In contrast, maraging steels are relatively soft and ductile initially but become hard, strong, and tough when aged. They are fabricated while ductile and later strengthened by an aging treatment. These steels have high resistance to corrosion, including stress-corrosion cracking.

(W. T. Lankford, Jr., ed., *The Making, Shaping and Treating of Steel,* Association of Iron and Steel Engineers, Pittsburgh, Pa.)

1.24 STEELMAKING METHODS

Structural steel is usually produced today by one of two production processes. In the traditional process, iron or ‘‘hot metal’’ is produced in a blast furnace and then further processed in a basic oxygen furnace to make the steel for the desired products. Alternatively, steel can be made in an electric arc furnace that is charged mainly with steel scrap instead of hot metal. In either case, the steel must be produced so that undesirable elements are reduced to levels allowed by pertinent specifications to minimize adverse effects on properties.

In a **blast furnace,** iron ore, coke, and flux (limestone and dolomite) are charged into the top of a large refractory-lined furnace. Heated air is blown in at the bottom and passed up through the bed of raw materials. A supplemental fuel such as gas, oil, or powdered coal is also usually charged. The iron is reduced to metallic iron and melted; then it is drawn off periodically through tap holes into transfer ladles. At this point, the molten iron includes several other elements (manganese, sulfur, phosphorus, and silicon) in amounts greater than permitted for steel, and thus further processing is required.

In a **basic oxygen furnace,** the charge consists of hot metal from the blast furnace and steel scrap. Oxygen, introduced by a jet blown into the molten metal, reacts with the impurities present to facilitate the removal or reduction in level of unwanted elements, which are trapped in the slag or in the gases produced. Also, various fluxes are added to reduce the sulfur and phosphorus contents to desired levels. In this batch process, large heats of steel may be produced in less than an hour.

An **electric-arc furnace** does not require a hot metal charge but relies mainly on steel scrap. The metal is heated by an electric arc between large carbon electrodes that project through the furnace roof into the charge. Oxygen is injected to speed the process. This is a versatile batch process that can be adapted to producing small heats where various steel grades are required, but it also can be used to produce large heats.

Ladle treatment is an integral part of most steelmaking processes. The ladle receives the product of the steelmaking furnace so that it can be moved and poured into either ingot molds or a continuous casting machine. While in the ladle, the chemical composition of the steel is checked, and alloying elements are added as required. Also, deoxidizers are added to remove dissolved oxygen. Processing can be done at this stage to reduce further sulfur content, remove undesirable nonmetallics, and change the shape of remaining inclusions. Thus significant improvements can be made in the toughness, transverse properties, and through-thickness ductility of the finished product. Vacuum degassing, argon bubbling, induction stirring, and the injection of rare earth metals are some of the many procedures that may be employed.

Killed steels usually are deoxidized by additions to both furnace and ladle. Generally, silicon compounds are added to the furnace to lower the oxygen content of the liquid metal and stop oxidation of carbon (block the heat). This also permits addition of alloying elements that are susceptible to oxidation. Silicon or other deoxidizers, such as aluminum, vanadium, and titanium, may be added to the ladle to complete deoxidation. Aluminum, vanadium, and titanium have the additional beneficial effect of inhibiting grain growth when the steel is normalized. (In the hot-rolled conditions, such steels have about the same ferrite grain size as semikilled steels.) Killed steels deoxidized with aluminum and silicon (**made to fine-grain practice**) often are used for structural applications because of better notch toughness and lower transition temperatures than semikilled steels of the same composition.

(W. T. Lankford, Jr., ed., *The Making, Shaping and Treating of Steel,* Association of Iron and Steel Engineers, Pittsburgh, Pa.)

1.25 CASTING AND HOT ROLLING

Today, the **continuous casting** process is used to produce semifinished products directly from liquid steel, thus eliminating the ingot molds and primary mills used previously. With continuous casting, the steel is poured from sequenced ladles to maintain a desired level in a tundish above an oscillating water-cooled copper mold (Fig. 1.15). The outer skin of the steel strand solidifies as it passes through the mold, and this action is further aided by water sprayed on the skin just after the strand exits the mold. The strand passes through sets of supporting rolls, curving rolls, and straightening rolls and is then rolled into slabs. The slabs

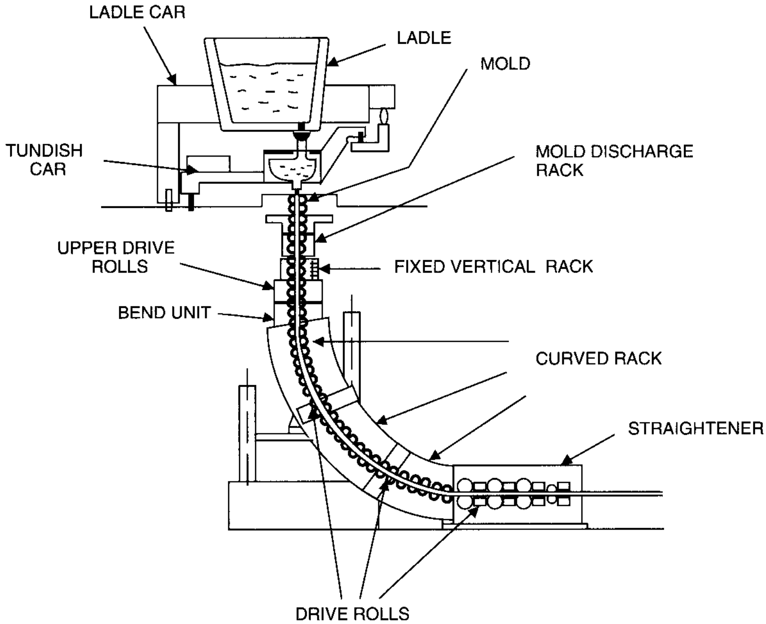

FIGURE 1.15 Schematic of slab caster.

are cut to length from the moving strand and held for subsequent rolling into finished product. Not only is the continuous casting process a more efficient method, but it also results in improved quality through more consistent chemical composition and better surfaces on the finished product.

Plates, produced from slabs or directly from ingots, are distinguished from sheet, strip, and flat bars by size limitations in ASTM A6. Generally, plates are heavier, per linear foot, than these other products. Plates are formed with straight horizontal rolls and later trimmed (sheared or gas cut) on all edges.

Slabs usually are reheated in a furnace and descaled with high-pressure water sprays before they are rolled into plates. The plastic slabs are gradually brought to desired dimensions by passage through a series of rollers. In the last rolling step, the plates pass through leveling, or flattening, rollers. Generally, the thinner the plate, the more flattening required. After passing through the leveler, plates are cooled uniformly, then sheared or gas cut to desired length, while still hot.

Some of the plates may be heat treated, depending on grade of steel and intended use. For carbon steel, the treatment may be annealing, normalizing, or stress relieving. Plates of HSLA or constructional alloy steels may be quenched and tempered. Some mills provide facilities for on-line heat treating or for thermomechanical processing (controlled rolling). Other mills heat treat off-line.

Shapes are rolled from continuously cast beam blanks or from blooms that first are reheated to 2250°F. Rolls gradually reduce the plastic blooms to the desired shapes and sizes. The shapes then are cut to length for convenient handling, with a hot saw. After that, they are cooled uniformly. Next, they are straightened, in a roller straightener or in a gag press. Finally, they are cut to desired length, usually by hot shearing, hot sawing, or cold sawing. Also, column ends may be milled to close tolerances.

ASTM A6 requires that material for delivery "shall be free from injurious defects and shall have a workmanlike finish." The specification permits manufacturers to condition plates and shapes "for the removal of injurious surface imperfections or surface depressions by grinding, or chipping and grinding. . . ." Except in alloy steels, small surface imperfections may be corrected by chipping or grinding, then depositing weld metal with low-hydrogen electrodes. Conditioning also may be done on slabs before they are made into other products. In addition to chipping and grinding, they may be scarfed to remove surface defects.

Hand chipping is done with a cold chisel in a pneumatic hammer. Machine chipping may be done with a planer or a milling machine.

Scarfing, by hand or machine, removes defects with an oxygen torch. This can create problems that do not arise with other conditioning methods. When the heat source is removed from the conditioned area, a quenching effect is produced by rapid extraction of heat from the hot area by the surrounding relatively cold areas. The rapid cooling hardens the steel, the amount depending on carbon content and hardenability of the steel. In low-carbon steels, the effect may be insignificant. In high-carbon and alloy steels, however, the effect may be severe. If preventive measures are not taken, the hardened area will crack. To prevent scarfing cracks, the steel should be preheated before scarfing to between 300 and 500°F and, in some cases, postheated for stress relief. The hardened surface later can be removed by normalizing or annealing.

Internal structure and many properties of plates and shapes are determined largely by the chemistry of the steel, rolling practice, cooling conditions after rolling, and heat treatment, where used. Because the sections are rolled in a temperature range at which steel is austenitic (see Art. 1.20), internal structure is affected in several ways.

The final austenitic grain size is determined by the temperature of the steel during the last passes through the rolls (see Art. 1.21). In addition, inclusions are reoriented in the direction of rolling. As a result, ductility and bendability are much better in the longitudinal direction than in the transverse, and these properties are poorest in the thickness direction.

The cooling rate after rolling determines the distribution of ferrite and the grain size of the ferrite. Since air cooling is the usual practice, the final internal structure and, therefore, the properties of plates and shapes depend principally on the chemistry of the steel, section size, and heat treatment. By normalizing the steel and by use of steels made to fine-grain practice (with grain-growth inhibitors, such as aluminum, vanadium, and titanium), grain size can be refined and properties consequently improved.

In addition to the preceding effects, rolling also may induce residual stresses in plates and shapes (see Art. 1.15). Still other effects are a consequence of the final thickness of the hot-rolled material.

Thicker material requires less rolling, the finish rolling temperature is higher, and the cooling rate is slower than for thin material. As a consequence, thin material has a superior microstructure. Furthermore, thicker material can have a more unfavorable state of stress because of stress raisers, such as tiny cracks and inclusions, and residual stresses.

Consequently, thin material develops higher tensile and yield strengths than thick material of the same steel chemistry. ASTM specifications for structural steels recognize this usually by setting lower yield points for thicker material. A36 steel, however, has the same yield point for all thicknesses. To achieve this, the chemistry is varied for plates and shapes and for thin and thick plates. Thicker plates contain more carbon and manganese to raise the yield point. This cannot be done for high-strength steels because of the adverse effect on notch toughness, ductility, and weldability.

Thin material generally has greater ductility and lower transition temperatures than thick material of the same steel. Since normalizing refines the grain structure, thick material improves relatively more with normalizing than does thin material. The improvement is even greater with silicon-aluminum-killed steels.

(W. T. Lankford, Jr., ed., *The Making, Shaping and Treating of Steel,* Association of Iron and Steel Engineers, Pittsburgh, Pa.)

1.26 EFFECTS OF PUNCHING HOLES AND SHEARING

Excessive cold working of exposed edges of structural-steel members can cause embrittlement and cracking and should be avoided. Punching holes and shearing during fabrication are cold-working operations that can cause brittle failure in thick material.

Bolt holes, for example, may be formed by drilling, punching, or punching followed by reaming. Drilling is preferable to punching, because punching drastically coldworks the material at the edge of a hole. This makes the steel less ductile and raises the transition temperature. The degree of embrittlement depends on type of steel and plate thickness. Furthermore, there is a possibility that punching can produce short cracks extending radially from the hole. Consequently, brittle failure can be initiated at the hole when the member is stressed.

Should the material around the hole become heated, an additional risk of failure is introduced. Heat, for example, may be supplied by an adjacent welding operation. If the temperature should rise to the 400 to 850°F range, strain aging will occur in material susceptible to it. The result will be a loss in ductility.

Reaming a hole after punching can eliminate the short, radial cracks and the risks of embrittlement. For that purpose, the hole diameter should be increased from $\frac{1}{16}$ to $\frac{1}{4}$ in by reaming, depending on material thickness and hole diameter.

Shearing has about the same effects as punching. If sheared edges are to be left exposed. $\frac{1}{16}$ in or more material, depending on thickness, should be trimmed, usually by grinding or machining. Note also that rough machining, for example, with edge planers making a deep cut, can produce the same effects as shearing or punching.

(M. E. Shank, *Control of Steel Construction to Avoid Brittle Failure,* Welding Research Council, New York.)

1.27 EFFECTS OF WELDING

Failures in service rarely, if ever, occur in properly made welds of adequate design.

If a fracture occurs, it is initiated at a notchlike defect. Notches occur for various reasons. The toe of a weld may form a natural notch. The weld may contain flaws that act as notches. A welding-arc strike in the base metal may have an embrittling effect, especially if weld metal is not deposited. A crack started at such notches will propagate along a path determined by local stresses and notch toughness of adjacent material.

Preheating before welding minimizes the risk of brittle failure. Its primary effect initially is to reduce the temperature gradient between the weld and adjoining base metal. Thus, there is less likelihood of cracking during cooling and there is an opportunity for entrapped hydrogen, a possible source of embrittlement, to escape. A consequent effect of preheating is improved ductility and notch toughness of base and weld metals, and lower transition temperature of weld.

Rapid cooling of a weld can have an adverse effect. One reason that arc strikes that do not deposit weld metal are dangerous is that the heated metal cools very fast. This causes severe embrittlement. Such arc strikes should be completely removed. The material should be preheated, to prevent local hardening, and weld metal should be deposited to fill the depression.

Welding processes that deposit weld metal low in hydrogen and have suitable moisture control often can eliminate the need for preheat. Such processes include use of low-hydrogen electrodes and inert-arc and submerged-arc welding.

Pronounced segregation in base metal may cause welds to crack under certain fabricating conditions. These include use of high-heat-input electrodes and deposition of large beads at slow speeds, as in automatic welding. Cracking due to segregation, however, is rare for the degree of segregation normally occurring in hot-rolled carbon-steel plates.

Welds sometimes are peened to prevent cracking or distortion, although special welding sequences and procedures may be more effective. Specifications often prohibit peening of the first and last weld passes. Peening of the first pass may crack or punch through the weld. Peening of the last pass makes inspection for cracks difficult. Peening considerably reduces toughness and impact properties of the weld metal. The adverse effects, however, are eliminated by the covering weld layer (last pass).

(M. E. Shank, *Control of Steel Construction to Avoid Brittle Failure,* Welding Research Council, New York; R. D. Stout and W. D. Doty, *Weldability of Steels,* Welding Research Council, New York.)

1.28 EFFECTS OF THERMAL CUTTING

Fabrication of steel structures usually requires cutting of components by thermal cutting processes such as oxyfuel, air carbon arc, and plasma arc. Thermal cutting processes liberate a large quantity of heat in the kerf, which heats the newly generated cut surfaces to very high temperatures. As the cutting torch moves away, the surrounding metal cools the cut surfaces rapidly and causes the formation of a heat-affected zone analogous to that of a weld. The depth of the heat-affected zone depends on the carbon and alloy content of the steel, the thickness of the piece, the preheat temperature, the cutting speed, and the postheat treatment. In addition to the microstructural changes that occur in the heat-affected zone, the cut surface may exhibit a slightly higher carbon content than material below the surface.

The detrimental properties of the thin layer can be improved significantly by using proper preheat, or postheat, or decreasing cutting speed, or any combination thereof. The hardness of the thermally cut surface is the most important variable influencing the quality of the surface as measured by a bend test. Plate chemistry (carbon content), Charpy V-notch toughness, cutting speed, and plate temperature are also important. Preheating the steel prior to cutting, and decreasing the cutting speed, reduce the temperature gradients induced by the cutting operation, thereby serving to (1) decrease the migration of carbon to the cut surface, (2) decrease the hardness of the cut surface, (3) reduce distortion, (4) reduce or give more favorable distribution to the thermally induced stresses, and (5) prevent the formation of quench or cooling cracks. The need for preheating increases with increased carbon and alloy content of the steel, with increased thickness of the steel, and for cuts having geometries that act as high stress raisers. Most recommendations for minimum preheat temperatures are similar to those for welding.

The roughness of thermally cut surfaces is governed by many factors such as (1) uniformity of the preheat, (2) uniformity of the cutting velocity (speed and direction), and (3) quality of the steel. The larger the nonuniformity of these factors, the larger is the roughness of the cut surface. The roughness of a surface is important because notches and stress raisers can lead to fracture. The acceptable roughness for thermally cut surfaces is governed by the job requirements and by the magnitude and fluctuation of the stresses for the particular component and the geometrical detail within the component. In general, the surface roughness requirements for bridge components are more stringent than for buildings. The desired magnitude and uniformity of surface roughness can be achieved best by using automated thermal cutting equipment where cutting speed and direction are easily controlled. Manual procedures tend to produce a greater surface roughness that may be unacceptable for primary tension components. This is attributed to the difficulty in controlling both the cutting speed and the small transverse perturbations from the cutting direction.

(R. L. Brockenbrough and J. M. Barsom, Metallurgy, Chapter 1.1 in *Constructional Steel Design—An International Guide,* R. Bjorhovde et al, Eds., Elsevier Science Publishers, Ltd., New York.)