Steel[1]

The use of iron dates back to about 1500 B.C. when primitive furnaces were used to heat the ore in a charcoal fire**.** Ferrous metals were produced on a relatively small scale until the blast furnace was developed in the eighteenth century. Iron products were widely used in the latter half of the eighteenth century and the early part of nineteenth century. Steel production started in the mid-1800s when the Bessemer converter was invented. In the second half of the nineteenth century steel technology advanced rapidly due to the development of the basic oxygen furnace and continuous casting methods. More recently, computer-controlled manufacturing has increased efficiency and reduced the cost of steel production.

Currently, steel and steel alloys are used widely in civil engineering applications. In addition, wrought iron is still used on a smaller scale for pipes, as well as blacksmith work. Cast iron is used for pipes, hardware, and machine parts subjected to tensile or dynamic loading.

Steel products used in construction can be classified as

1. *structural steel* for use in plates, bars, pipes, structural shapes, etc.,
2. *reinforcing steel* (rebars) for use in concrete reinforcement,
3. miscellaneous for use in such applications as forms and pans.

Civil and construction engineers rarely have the opportunity to formulate steel with specific properties. Rather, they must select existing products from suppliers. Even the shapes for structural elements are generally restricted to those readily available from manufacturers. While specific shapes can be made to order, the cost to fabricate low-volume members is generally prohibitive. Therefore, the majority of engineering projects are designed using standard steel types and structural shapes.

Even though civil and construction engineers are not responsible for formulating steel products, they still must understand how steel is manufactured and treated and how it responds to loads and environmental conditions.

The steel production process can be described as having three main phases: the reduction of iron ore to pig iron; refining the pig iron to steel, and the forming of steel into various products.

Reduction of the iron ore to pig iron takes place in a blast furnace. The ore is heated in the presence of carbon. Oxygen in the ore reacts with carbon to form gases. The molten iron with an excess of carbon in solution collects at the bottom of the furnace. The excess carbon must be removed to produce high-grade steel. Three types of furnaces are used for refining pig iron to steel: open hearth; basic oxygen; and electric arc. Regardless of the refining process, the molten steel with the desired chemical composition is then either cast into ingots or cast continuously into a desired shape. The ingot must be reheated prior to shaping the steel into the final product.

In refining steel from iron ore, the quantity of carbon used must be carefully controlled in order for the steel to have the desired properties. Wrought iron has less than 0.1 percent carbon; cast iron has more than 2 percent carbon, and steel has less than 2 percent carbon. Increasing the carbon content increases strength but reduces ductility. The elasticity of the steel is unaffected by the carbon content.

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[1] Modified from “Materials for Civil and Construction Engineers” by M.S Mamlouk and J.P Zaniewski.

Iron can exist in various solid phases depending on the carbon content and temperature. The relative proportions of these formations significantly affect the properties of the final product. Specific changes to the properties of steel can be achieved by altering the rate of cooling of the molten steel.

Heat Treatment of Steel

The properties of steel can be altered by applying a variety of heat treatments. For example, steel can be hardened or softened by using heat treatment. The response of steel to heat treatment depends upon its alloying composition. Common heat treatments employed for steel include annealing, normalising, hardening, and tempering.

Annealing

Annealing is performed by heating the metal to the austentite stable range (10 deg above the austentite line), and holding it at that temperature for the proper period. The material is then slowly cooled to room temperature. The objectives of annealing are to refine the grain, soften the steel, remove internal stresses, remove gases; increase ductility and toughness, and change electrical and magnetic properties.

Normalizing

Normalizing is similar to annealing, with a slight difference in heating temperature. Steel is normalized by heating it into the austentizing range, usually 40 deg above the austenite line. The material is then air cooled. Normalizing produces a uniform fine-grained microstructure. Therefore, normalizing is regarded as a corrective treatment, and not a strengthening or hardening treatment. Normalizing is used in structural plate production to produce high-fracture toughness.

Hardening

Steel is hardened by heating it to a temperature above the transformation range and holding it until austentite is formed. The steel is then quenched (cooled rapidly) by plunging it into water, brine or oil. Quenching hardens the steel, and hardening puts the steel in a state of strain. This strain sometimes causes steel pieces with sharp angles or grooves to crack immediately after hardening. Thus hardening must be followed by tempering.

Tempering

Tempering involves reheating a hardened steel to a definite temperature below the critical temperature, holding it for a time, and cooling it, usually by quenching. Tempering increases ductility and toughness.

Steel Alloys

Alloy metals can be used to alter the characteristics of steel. By some counts there are as many as 250,000 different alloys of steel produced. Of these as many as 200 may be used for civil engineering applications. Rather than go into the specific characteristics of selected alloys, the general effect of different alloying agents will be presented. Alloy agents are added to improve one or more of the following properties:

1. hardenabflity
2. corrosion resistance
3. machineability
4. ductility
5. strength

Common alloy agents, their typical percentage range, and their effects are summarized in the following table.

	Typical Ranges in Alloy Steels, %	**Principal Effects**
Aluminum	<2	Aids nitriding Restricts grain froth Removes oxygen in steel melting
Sulfur	< 0.5	Adds machinability Reduces weldability and ductility
Chromium	0.3 to 0.4	Increases resistance to corrosion and oxidation Increases hardenability Increases high-temperature strength Can combine with carbon to form hard wear-resistant microconstituents
Nickel	0.3 to 5.0	Promotes an austenitic structure Increases hardenability Increases toughness
Copper	0.2 to 0.5	Promotes tenacious oxide film to aid atmospheric corrosion resistance
Manganese	0.3 to 2.0	Increases hardenability Promotes an austenitic structure Combines with sulfur to reduce its adverse effects
Silicon	0.2 to 2.5	Removes oxygen in steel-making Improves toughness Increases hardenability
Molybdenum	0.1to 0.5	Promotes grain rennement Increases hardenability Improves high-temperature strength
Vanadium	0.1 to 0. 3	Promotes grain rennement Increases hardenability Combines with carbon to form wear-resistant microconstituents

By altering the carbon and alloy content and by using different heat treatments, steel can be produced with a wide variety of characteristics. These are classified as:

1. Low alloy
    - Low carbon
        - Plain
        - High-strength low alloy
    - Medium carbon

    - Plain
    - Heat treatable
  - High carbon
    - Plain
    - Tool

2. High alloy
   - Tool
   - Stainless steel

Steel used for construction are typically low and medium carbon plain steels. Stainless steel has been used in some highly corrosive applications such as in concrete pavements, and steel components in swimming pools and drainage lines.

Structural Steel

Structural steel is used in hot-rolled structural shapes, plates, and bars. Structural steel is used for various types of structural members such as columns, beams, bracings, frames, trusses, bridge girders, and other structural applications.

Structural Steel Grades

Structural steel is produced in the United States in six grades: A36, A529, A572, A242, A588, and A514. The following table shows the chemical and tensile requirements of these grades as specified by ASTM standards. Structural steels have a carbon content in the range of 0.15% to 0.27%. All structural steels are alloyed with a small amount of copper. All but A36 contain manganese.

Grade A36 is a structural carbon steel with a tensile yield stress of 250 MPa (36 ksi). Grade A529 is a structural steel with a minimum yield stress of 290 MPa (42 ksi), while other grades are high-strength steels with higher yield stresses, as shown in the table. Grades A242 and A588 are corrosion-resistant, high-strength, low-alloy structural steels.

Grade A36 is the most commonly used steel in buildings, bridges, transmission towers, and other structures. It is available in plates, structural shapes, and bars. It offers satisfactory performance in various temperature conditions since it does not experience brittle fracture at low temperatures. High-strength steel results in lighter sections that can prove to be economical, especially for tension members and beams in continuous and composite construction. Because of their corrosion resistance, Grades A242 and A588 can be used in the uncoated condition in most atmospheres. When these two grades are coated, they produce longer coating lives than other grades. Although corrosion-resistant steel grades have high initial cost, they are used to lower maintenance costs over the life of the structure.

Sectional Shapes

Various cross-sectional shapes are commonly used in structural applications. These shapes are produced in different sizes and designated with the letters W, HP, M, S, C, MC, and L. W shapes are doubly symmetric wide-flange shapes whose flanges are substantially parallel. HP shapes are also wide-flange shapes whose flanges and webs are of the same nominal thickness and whose depth and width are essentially the same. The S shapes are doubly symmetric shapes whose inside flange surfaces have approximately 16.67% slope. The M shapes are doubly symmetric shapes that cannot be classified as W, S, or HP shapes, C shapes are channels with inside flange surfaces having a slope of an approximately 16.67%. MC shapes are channels that cannot be classified as C shapes. L shapes are angle shapes with either equal or unequal legs. In addition to these shapes, other structural sections are available, such as tee, sheet piling, and rail. The W, M, S, HP, C, and MC shapes are designated by a letter, followed by two numbers separated by an x. The letter indicates the shape, while the two numbers indicate the nominal depth and the weight per linear unit length. For example, W 44 x 335 means W shape with a nominal depth of 44 in. and a weight of 335 lb/linear foot. An angle is designated with the letter L, followed by three numbers that indicate the leg dimensions and thickness in inches, such as L 4 x 4 x 1/2. Dimensions of these structural shapes are controlled by ASTM A6/A6M.

			***Chemical Requirements,* %**			***Tensile Requirements***		
ASTM Designation	**Type**	**Gradet**	**Carbon (max.)**	**Manganese (max.)**	**Copper (min.)**	**Tensile strength, MPa (ksi)**	**Yield Point (min.), MPa (ksi)**	**Availability**
A36	Structural carbon steel	36	0.26	-	0.20	400-550 (58-80)	250 (36)	All shapes, plates, and bars
A529	Structural steel with 42 ksi min. yield point	42	0.27	1.2	0.20	415-485 (60-85)	290 (42)	Selected shapes, plates, and bars < 1/2 in. thick
A572	High-strength low-alloy steel of structural quality	42	0.21	1.35	0.20	415 (60)	290 (42)	All shapes, sheet piling, and tees
		50	0.23	1.35	0.20	450 (65)	345 (50)	All shapes, sheet piling, and tees
		60	0.26	1.35	0.20	52 0 (75)	41 5 (60]	Limited shapes, all sheet piling, and tees
		65	0.26	1.35	0.20	550 (80)	450 (65)	Limited shapes and all tees
A242	High strength low-alloy structural steel (corrosion resistant)	42-50	0.15	1.0	0.20	435 480 (63-70)	290-345 (42-50)	Limited shapes, plates, and bars
A588	High-strength low-alloy structural steel with 50 ksi min. yield point (corrosion resistant)	50	0.1 7-0.1 9	0.5-1.25	0.2-0.5	485 (70) 435-485 (63-70)	345 (50) 290-345 (42-50)	All shapes, plates, and bars
A514	High-yield strength quenched and tempered alloy steel	90-100	0.1 2-0.21	0.4-1.10	0.1 5-0.50	690-895 (100-1 30)	290-690 (90-1 I 0)	Plates

W shapes are commordy used as beams and columns, HP shapes are used as bearing piles, and S shapes are used as beams or girders. Composite sections can also be formed by welding different shapes to use in various structural applications. Sheet piling sections are connected to each other and used as retaining walls.

Reinforcing Steel

Since concrete has negligible tensile strength, structural concrete members subjected to tensile and flexural stresses must be reinforced. Either conventional or prestressed reinforcing can be used, depending on the design situation. In conventional reinforcing, the stresses fluctuate with loads on the structure. This does not place any special requirements on the steel. On the other hand, in prestressed reinforcement the steel is under continuous tension. Any stress relaxation will reduce the effectiveness of the reinforcement. Hence special steels are required.

Reinforcing steel (rebars) is manufactured in three forms: plain *bars*, *deformed* bars, and plain and *deformed wire fabrics.* Plain bars are round without surface deformations. Plain bars provide only limited bond with the concrete and, therefore, are not typically used in sections subjected to tension or bending. Deformed bars have protrusions (deformations) at the surface, thus they ensure a good bond between the bar and the concrete. The deformed surface of the bar prevents slipping, allowing the concrete and steel to work as one unit. Wire fabrics are flat sheets in which wires pass each other at right angles, and one set of elements is parallel to the fabric axis. Plain wire fabrics develop the anchorage in concrete at the welded intersections, while deformed wire fabrics develop anchorage through deformations and at the welded intersections.

Deformed bars are used in concrete beams, slabs, columns, walls, footings, pavements, and other concrete structures, as well as in masonry construction. Welded wire fabrics are used in some concrete slabs and pavements, mostly to resist temperature and shrinkage stresses. Welded wire fabrics can be more economical to place, and thus allow for closer spacing of bars than is practical with individual bars.
Reinforcing steel is produced in the standard sizes shown in the following table. Bars are made of four types of steel: A615 (billet), A616 (rail), A617 (axle), and A706 (low alloy). Billet steel is the most widely used. Reinforcing steel is produced in four grades: 40, 50, 60, and 75, with yield stresses of 276 MPa, 345 MPa, 414 MPa, and 517 MPa (40 ksi, 50 ksi, 60 ksi, and 75 ksi), respectively.

Prestressed concrete requires special prestressing wires, strands, cables, and bars. Steel for prestressed concrete reinforcement must be of high strength and low relaxation properties. High-carbon steels and high-strength alloy steels are used for this purpose. Properties of prestressed concrete reinforcement are presented in ASTM specification A416 and AASHTO specification M203. These specifications define the requirements for a seven-wire uncoated steel strand. The specifications allow two types of steel, stress-relieved (normal-relaxation) and low-relaxation. Relaxation refers to the percent of stress reduction that occurs when a constant amount of strain is applied over an extended time period. Both stress-relieved and low-relaxation steels can be specified as Grade 250 or Grade 270, with ultimate strengths of 1725 MPa (250 ksi) and 1860 MPa (270 ksi), respectively. The specifications for this application are based on mechanical properties only; the chemistry of wires is not pertinent to this application. After stranding, low-relaxation strands are subjected to a continuous thermal-mechanical treatment to produce the required mechanical properties.

		Nominal Dimensions			Deformation Requirements (mm)		
Bar Designation Number	Nominal Mass, kg/m	Diameter, mm	Cross-sectional Area, mm2	Perimeter, mm	Maximum Average Spacing	Minimum Average Height	Maximum Gap
10 (3)	0,560	9.5	71	29.9	6.7	0.38	3.6
1 3 (4)	0,994	12.7	129	39.9	8.9	0.51	4.9
1 6 (5)	1,552	15.9	199	49.9	11.1	0.71	6.1
1 9 (6)	2,235	19.1	284	59.8	13.3	0.97	7.3
22 (7)	3,042	22.2	387	69.8	15.5	1.12	8.5
25 (8)	3.97325.4	510	79.8	17.8	1.27	9.7	
29 (9)	5.05928.7	645	90.0	20.1	1.42	10.9	
32 (10)	6,404	32.3	819	101.3	22.6	1.63	12.4
36 (11)	7,907	35.8	1006	112.5	25.1	1.80	15.7
43 (I 4)	11.3843.0	1452	135.1	30.1	2.16	16.5	
57 (l 8)	20.2457.3	2581	180.1	40.1	2.59	21.9	

ASTM Designation	Type	Grade	Tensile Strength (min.), MPa (ksi)	Yield Strengtht (min.), MPa (ksi)	Size Availability No.
A61 5	Billet steel bars (plain and deformed)	40	483 (70)	276 (40)	3-6
		60	620 (90)	41 4 (60)	3-1 8
		75	689 (1 00)	517 (75)	11 -1 8
A6]6	Rail steel (plain and deformed)	50	552 (80)	345 (50)	3-11
		60	620 (90)	414 (60)	3-11
A617	Axle steel (plain and deformed)	40	483 (70)	276 (40)	3 11
		60	620 (90)	41 4 (60)	3-11
A706	Low alloy steel bars, (deformed)	60	552 (80)	41 4-538 (60-78)	3-1 8