Steel as a Construction Material

Chapter

15

Iron and steel history

- The development of steel can be traced back to the beginning of the Iron Age (1200BC).
- Steel production in large scale started in the 18th century, after the blast furnace and the Bessemer converter was invented.

- In the second half of the 19th 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 the efficiency and reduced the cost of steel production.

Steel Advantages & limitations

Advantages

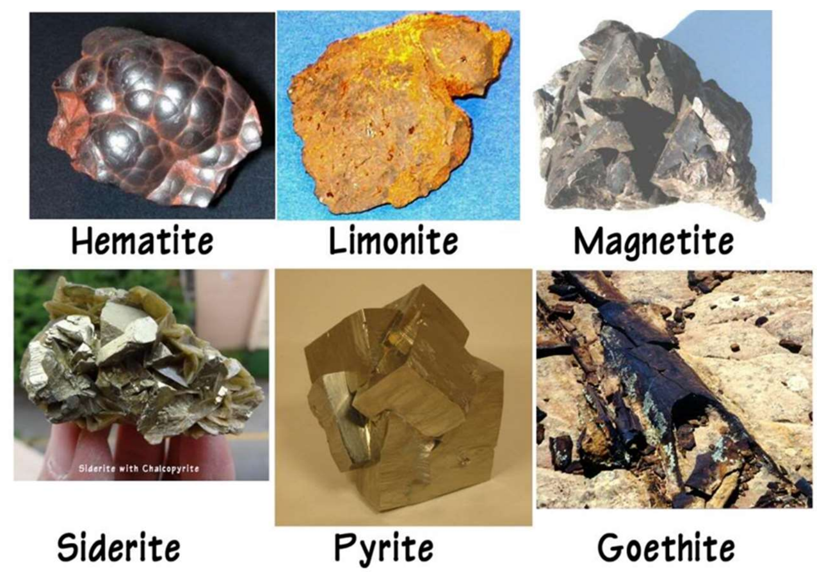
- High strength, ductility, the ability to carry tensile as well as compressive loads (light building weight).
- The ability to join members either with welding or mechanical fastening (less construction time).
- The properties of steel can be tailored through alloying and heat treatments.

Limitations

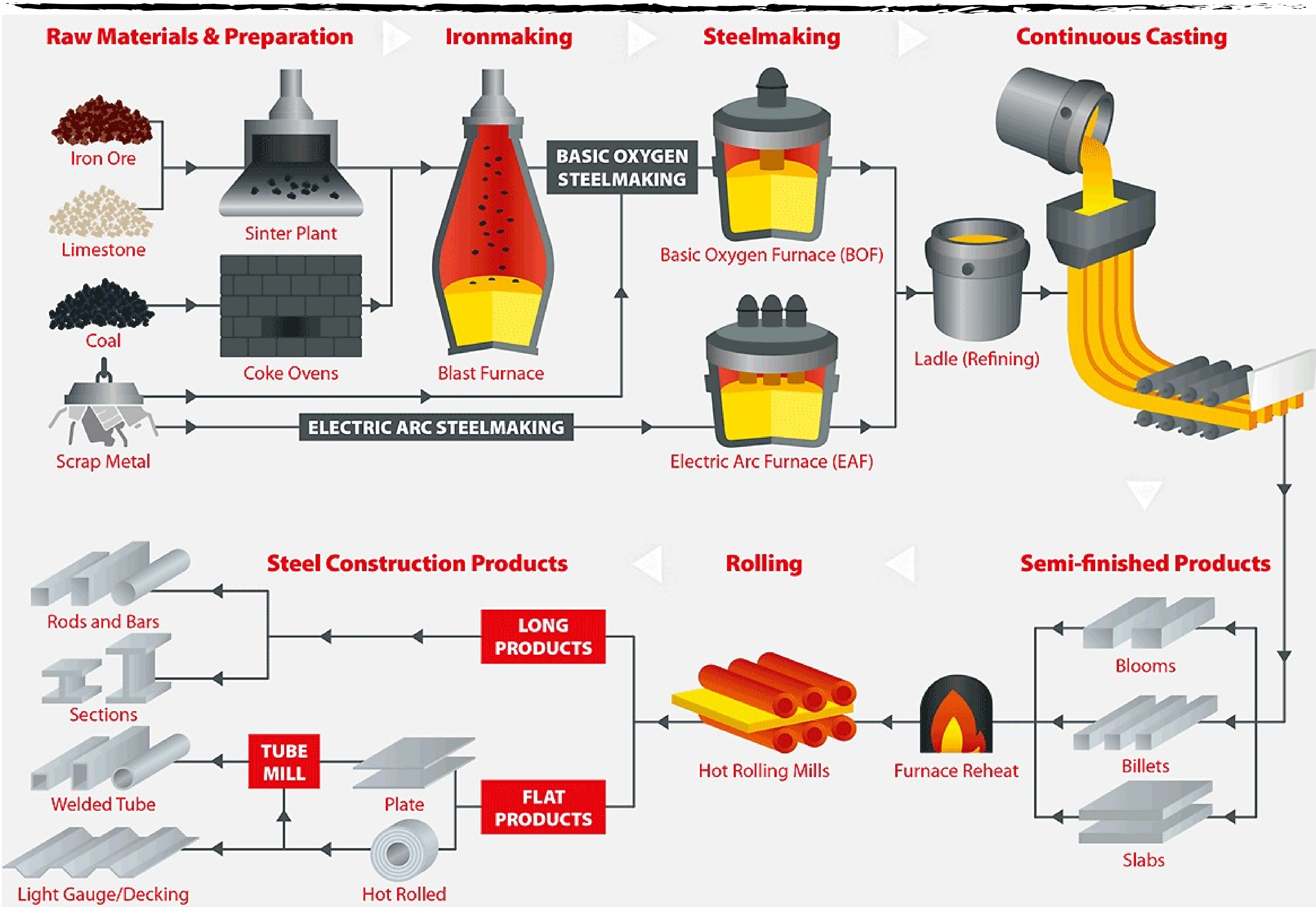
- Tendency to corrode.
- Engineers rarely have the opportunity to formulate steel with specific properties including shapes for structural elements which are generally restricted to those readily available from manufacturers.

Iron Ores

- Most common ores are: Magnetite (Fe_3O_4, 72.4% Fe); Hematite (Fe_2O_3, 69.9% Fe); Goethite ($FeO(OH)$, 62.9% Fe), Limonite ($FeO(OH)\cdot n(H_2O)$) or Siderite ($FeCO_3$, 48.2% Fe).
- Ores containing very high quantities of hematite or magnetite (greater than about 60% iron) are known as "natural ore" or "direct shipping ore", meaning they can be fed directly into iron-making blast furnaces.

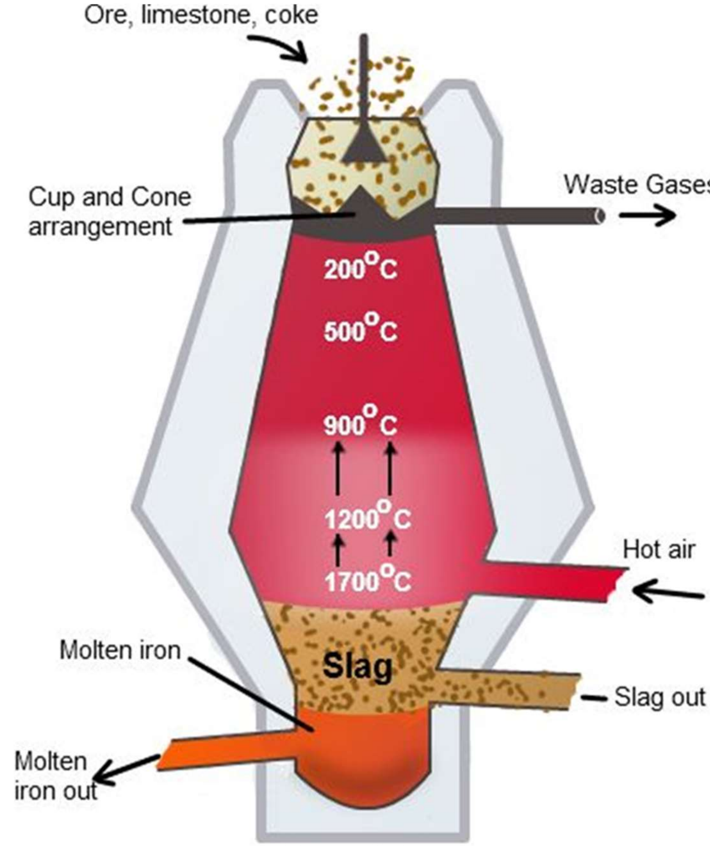


The Overall Process of Steel Production



Ironmaking - Reducing iron ore to pig iron

- In the blast furnace (see figure), the ore is heated in the presence of coal (coke) & limestone. Oxygen in the ore reacts with carbon to form gases.
- The coke, supplies carbon used to reduce iron oxides in the ore, Limestone is used to help remove impurities.
- The pig iron, which contains about 4 per cent of carbon, is industrially useless unless processed further to cast iron, wrought iron or steel.



Steelmaking

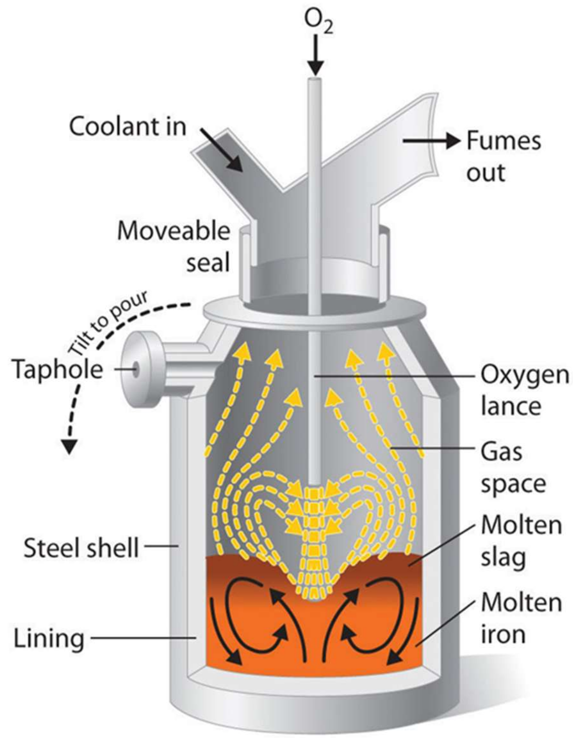
- The excess carbon in big iron , along with other impurities, must be removed to produce high-quality steel through a process of controlled oxidation at temperatures up to 1650 °C as shown by the following equation

$$2Fe[C] + O_2 \leftrightarrow 2Fe + 2CO$$

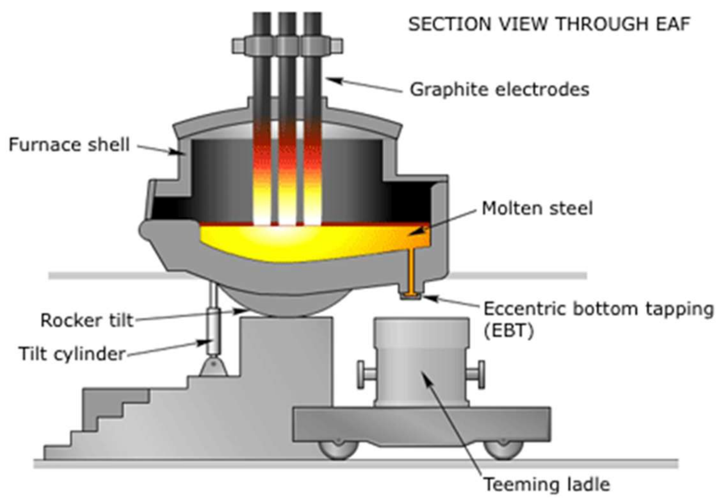
- Two types of furnaces are used for refining pig iron to steel: basic oxygen and electric arc.
- During the steel production process, oxygen may become dissolved in the liquid metal. As the steel solidifies, the oxygen can combine with carbon to form carbon monoxide bubbles
- Deoxidizing agents, such as aluminum is usually used to eliminate the formation of the bubbles. Completely deoxidized steels are known as killed steels

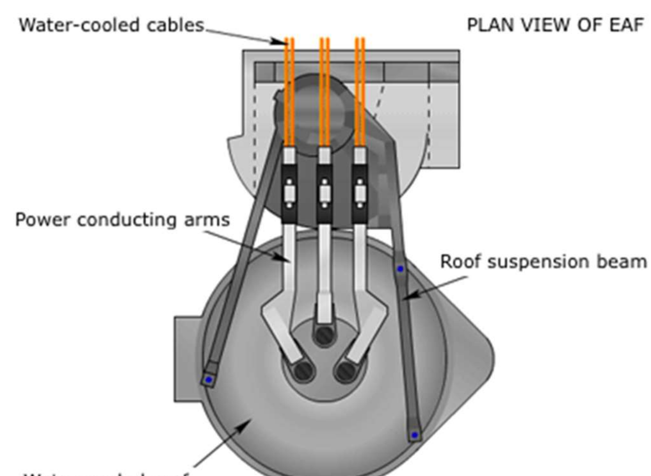
Steelmaking Furnaces

Basic oxygen furnace



Electric arc furnace

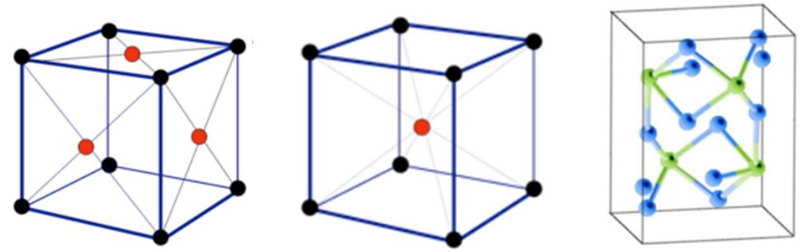




Source: steeluniversity org

Effect of carbon content in steel properties

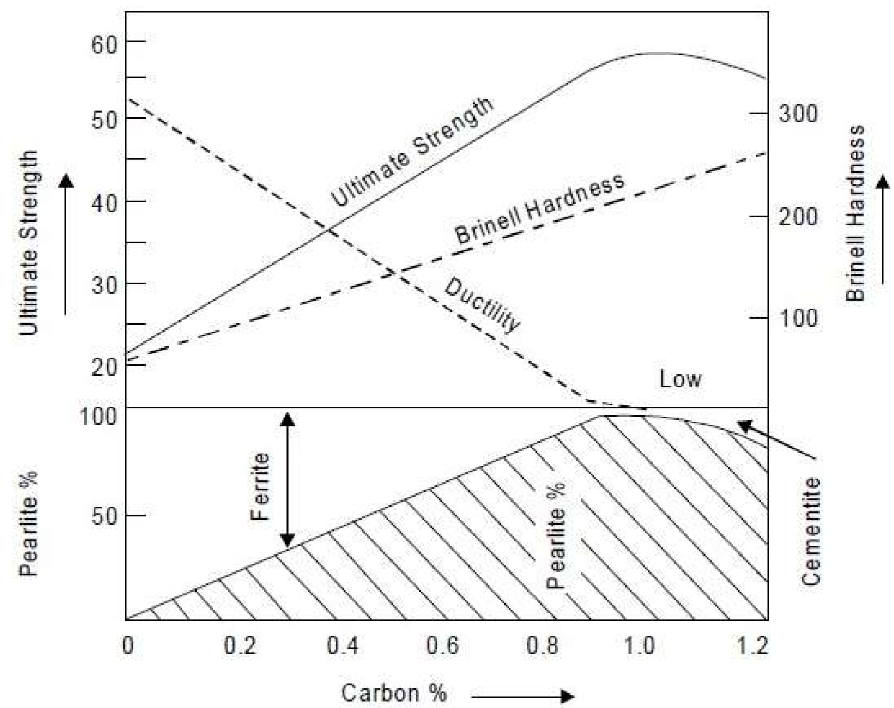
- As shown in the figure increasing the carbon content in steel will:
    - increased hardness
    - increased strength to certain limit
    - decreased weldability
    - decreased ductility
    - affect Machinability - about 0.2 to 0.25% C provides the best machinability
- Under 2% carbon is called steel, over 2% carbon is heading into the cast iron range.



Austenite　Ferrite　Cementite (Fe_3C)

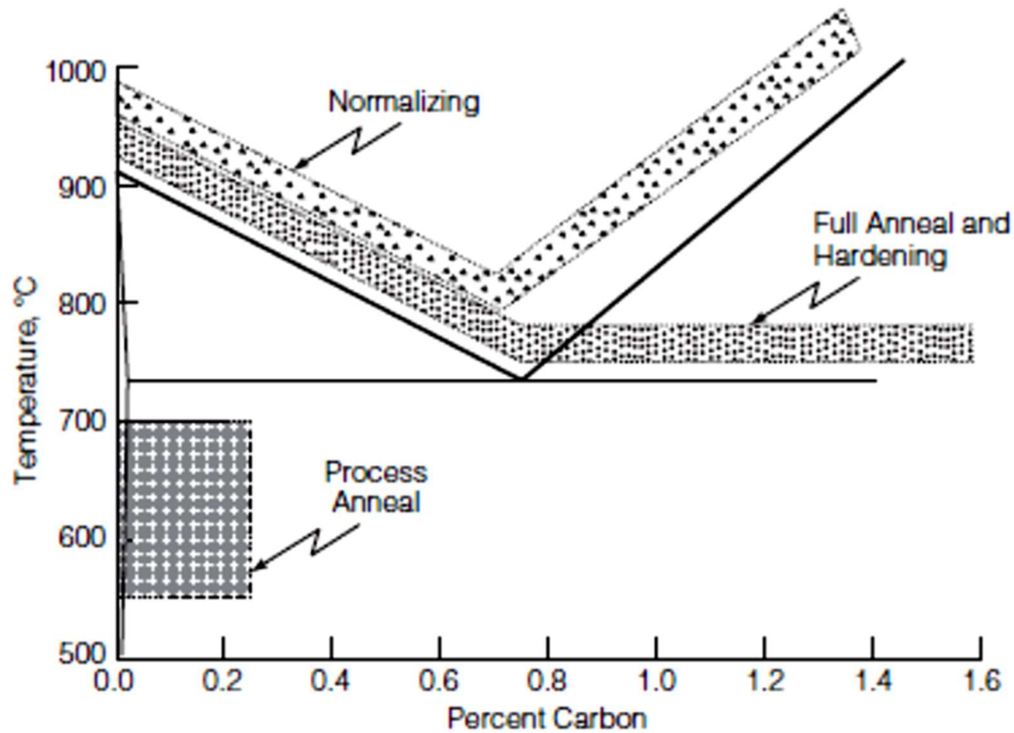
Perlite: a structure consists of alternate layers of ferrite and cementite.

Crystal structures of austenite, ferrite and cementite (iron carbide)



Heat Treatment of Steel

- Heat treatment may be defined as: the operation or combination of operations involving heating and cooling of steel in solid state to obtain desirable conditions or properties.
- Common heat treatments employed for steel include annealing, normalizing, hardening, and tempering.
- The response of steel to heat treatment depends upon its alloy composition.
- The temperatures ranges used for each of the treatment types are shown in the figure



Heat treatment temperatures.

Common heat treatment methods

- **Annealing**

Heating and controlled cooling used to refine the grain, soften the steel, remove internal stresses, remove gases, increase ductility and toughness, and change electrical and magnetic properties.

- **Normalizing**

Similar to annealing, with a slight difference in the temperature and the rate of cooling. Produces a uniform, fine-grained microstructure

- **Hardening**

Heating then rapid cooling which locks the iron into a BCC structure, (martensite) that has a very hard and brittle structure.

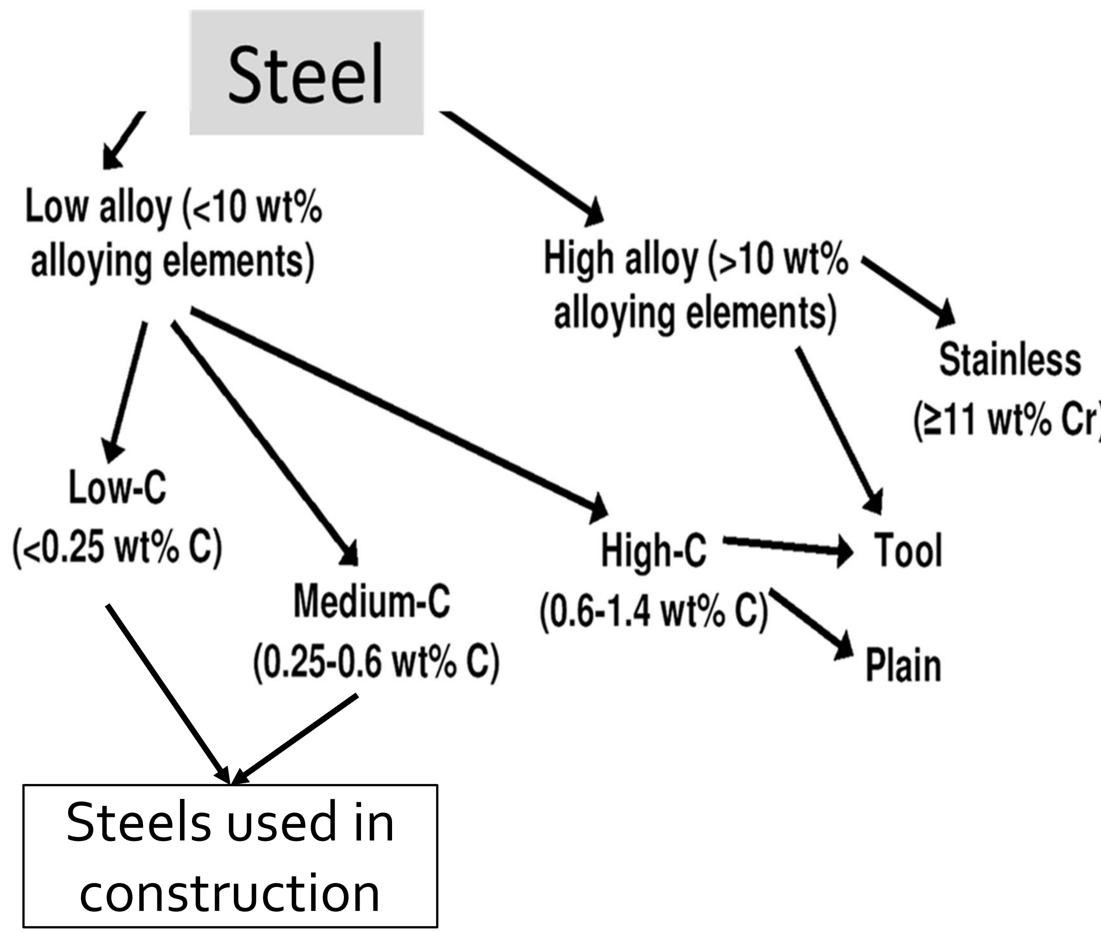
- **Tempering**

Hardening must be followed by tempering to improve ductility and toughness of steel. Steel reheated by immersion in either oil or nitrate salts for about two hours and then cooled in still air.

Steel Alloys

- Steel is mainly an alloy of iron and carbon, however other elements such as Aluminum, Nickel, Chromium …etc, can be added to alter the characteristics of steel further.

- Alloy agents are added to improve one or more of the following properties:
  - Hardenability.
  - Corrosion resistance.
  - Machinability.
  - Ductility.
  - Strength



Common steel alloying agents

	Typical Ranges in Alloy Steels (%)	Principal Effects
Aluminum	< 2	Aids nitriding Restricts grain froth Removes oxygen in steel melting
Sulfur	<0.05	Adds machinability Reduces weldability and ductility
Chromium	0.3 to 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	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	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	0.1 to 0.5	Promotes grain refinement Increases hardenability Improves high-temperature strength
Vanadium	0.1 to 0.3	Promotes grain refinement Increases hardenability Will combine with carbon to form wear-resistant microconstituents

Structural steel

- Structural steel is a category of steel construction material that is produced with a particular cross section or shape, and some specified values of strength and chemical composition.
- Structural steel is used for various types of structural members, such as columns, beams, bracings, frames, trusses, bridge girders, and other structural applications.
- Due to the widespread use of steel in many applications, there are a wide variety of systems for identifying or designating steel, based on grade, type and class. Virtually every country with an industrial capacity has specifications for steel

American structural steel grades

- Steels used for building construction in the US use standard alloys identified and specified by ASTM. These steels have an alloy identification beginning with A and then two, three, or four numbers.
- The principal types of structural steel include the following:
  - A36 Carbon Structural Steel.
  - A572 High-Strength Low-Alloy Structural Steel.
  - A588 Corrosion-Resistant High-Strength Low-Alloy Structural Steel.

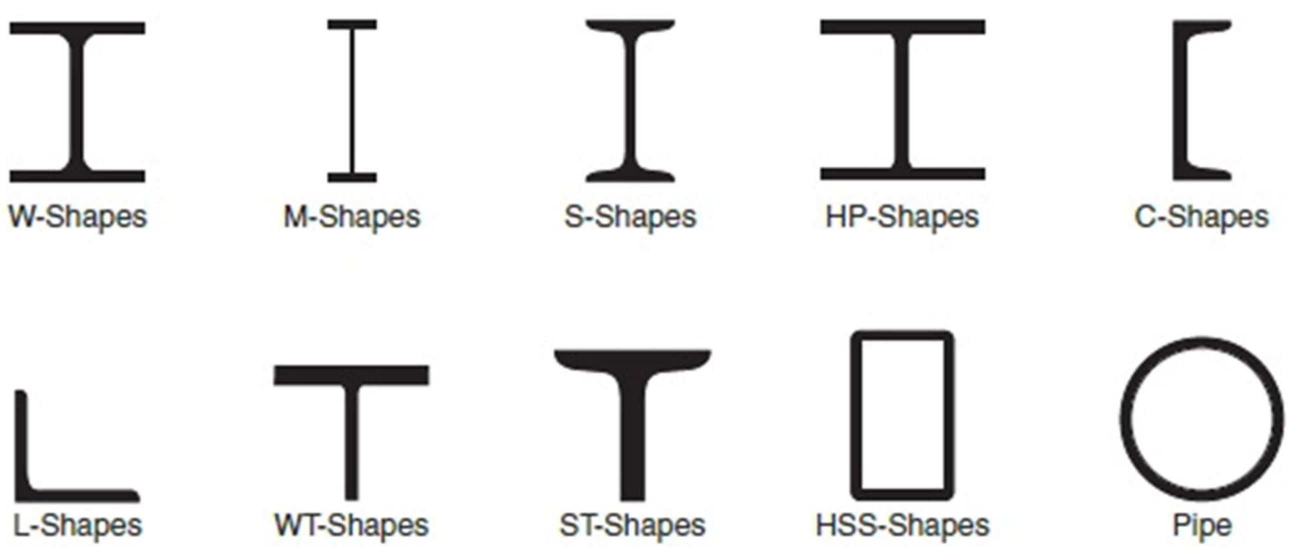
American structural steel grades

Steel Type	ASTM Designation		F_y[1] (ksi)	F_u[1] (ksi)	Minimum Elongation[2] (%)	Typical Chemical Composition[3] (%) C	Cu[5]	Mn	P	S	Ni	Cr	Si	Mo	V
Carbon	A36		36	58–80	23	0.26	0.2	0.8–1.2[6]	0.04	0.05					
	A53 Gr. B		35	60		0.25	0.4	0.95	0.05	0.045	0.4	0.4		0.15	0.08
	A500	Gr. B	42 46	58 58	23	0.3	0.18		0.045	0..045					
		Gr. C	46 50	62 62	21	0.27	0.18	1.4	0.045	0.045					
	A501		36	58	23	0.3	0.18		0.045	0.045					
	A529	Gr.50 Gr.55	50 55	65–100 70–100	19	0.27	0.2	1.35	0.04	0.05					
High-strength Low-alloy	A572	Gr. 42	42	60	24	0.21	-	1.35	0.04	0.05			0.15–0.4		
		Gr. 50	50	65	21	0.23	-	1.35	0.04	0.05			0.15–0.4		
		Gr. 55	55	70		0.25	-	1.35	0.04	0.05			0.15–0.5		
		Gr. 60	60	75	18	0.26	-	1.35	0.04	0.05			0.4		
		Gr. 65	65	80	17	0.23	-	1.65	0.04	0.05			0.4		
	A618	Gr. I&II	50	70	22	0.2	0.2	1.35	0.04	0.05					
		Gr. III	46	67	22	0.23	-	1.35	0.04	0.05			0.3		
	A913	50	50	65	21	0.12	0.45	1.6	0.04	0.03	0.25	0.25	0.4	0.07	0.06
		65	65	80	17	0.16	0.35	1.6	0.03	0.03	0.25	0.25	0.4	0.07	0.06
	A992[4]		50–65	65	18	0.23	0.6	0.5–1.5	0.04	0.05			0.4	0.15	0.11
Corrosion resistant High-strength low-alloy	A242	50	50	70	21	0.15	0.2	1	0.15	0.05					
	A588		50	70	21	0.19	0.25–0.4	0.8–1.25	0.04	0.05	0.4	0.4–0.65		0.02–0.1	

[1]Minimum values unless range or other control noted
[2]Two inch gauge length
[3]Maximum values unless range or other control noted
[4]A maximium yield to tensile strength ratio of 0.85 and carbon equivalent formula are included as mandatory in ASTM A992
[5]Several steel specifications can include a minimum copper content to provide weather resistance
[6]Range for plate given in table, bar range 0.6–0.9

American standards steel sections

- Structural steel in US is produced in different shapes as shown in the figure. These shapes are produced in different sizes and are designated with the letters W, HP, M, S, C, MC, and L.
- The most common shapes used in building construction are Wide Flange (W-flange), Channels (C-shape), Angles (L-shape), and Hollow Structural Sections (HSS).



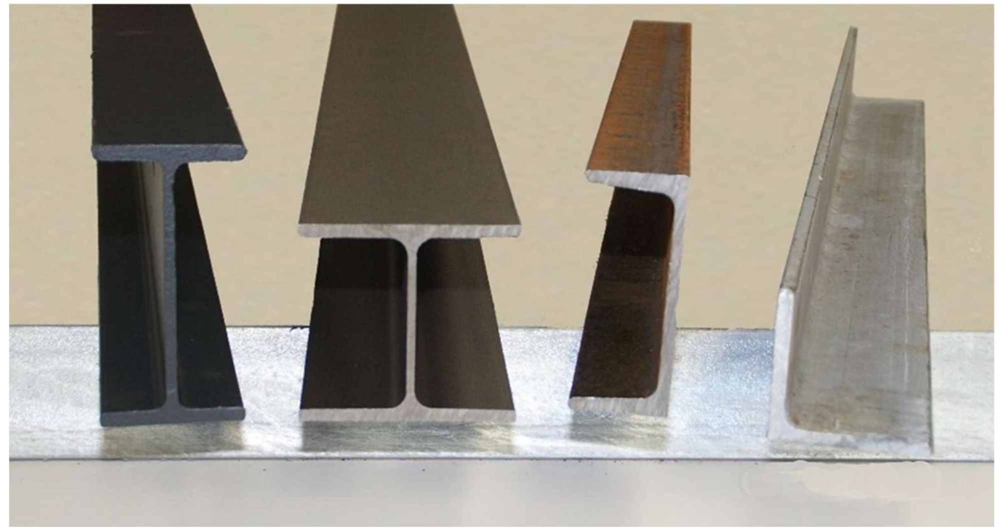
European steel grades

According to European standard steel is categorized in four major categories based on yield strength. each category includes several types of steel distinguish by their toughness, method of treatment and ability to resist weathering.

Designation		Method of deoxidation [b]	C in % max. for nominal product thickness in mm			Si % max.	Mn % max.	P % max. [d]	S % max. [d e]	N % max. [f]	Cu % max. [g]	Other % max. [h]
According EN 10027-1 and CR 10260	According EN 10027-2		≤ 16	> 16 ≤ 40	> 40[c]							
S235JR	1.0038	FN	0,17	0,17	0,20	-	1,40	0,035	0,035	0,012	0,55	-
S235J0	1.0114	FN	0,17	0,17	0,17	-	1,40	0,030	0,030	0,012	0,55	-
S235J2	1.0117	FF	0,17	0,17	0,17	-	1,40	0,025	0,025	-	0,55	-
S275JR	1.0044	FN	0,21	0,21	0,22	-	1,50	0,035	0,035	0,012	0,55	-
S275J0	1.0143	FN	0,18	0,18	0,18[i]	-	1,50	0,030	0,030	0,012	0,55	-
S275J2	1.0145	FF	0,18	0,18	0,18[i]	-	1,50	0,025	0,025	-	0,55	-
S355JR	1.0045	FN	0,24	0,24	0,24	0,55	1,60	0,035	0,035	0,012	0,55	-
S355J0	1.0553	FN	0,20[j]	0,20[k]	0,22	0,55	1,60	0,030	0,030	0,012	0,55	-
S355J2	1.0577	FF	0,20[j]	0,20[k]	0,22	0,55	1,60	0,025	0,025	-	0,55	-
S355K2	1.0596	FF	0,20[j]	0,20[k]	0,22	0,55	1,60	0,025	0,025	-	0,55	-
S450J0[l]	1.0590	FF	0,20	0,20[k]	0,22	0,55	1,70	0,030	0,030	0,025	0,55	[m]

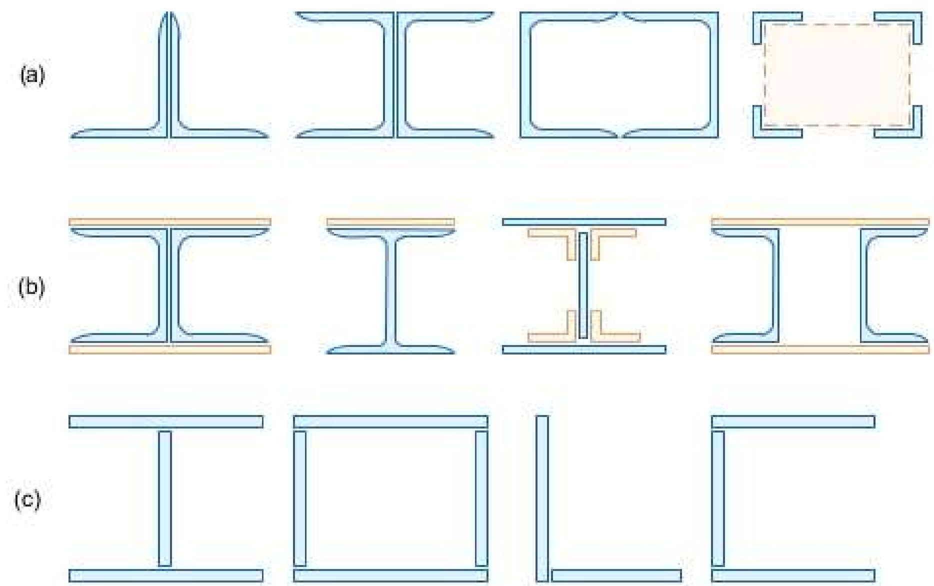
European steel sections

- I-beam it includes the IPE, HE, HL, HD and other sections;
- Z-Shape (half a flange in opposite directions)
- HSS-Shape (Hollow structural section) and including square, rectangular, circular (pipe)
- Angle (L-shaped cross-section)
- Structural channel (C cross-section).
- Tee (T-shaped cross-section)



Built Up Sections

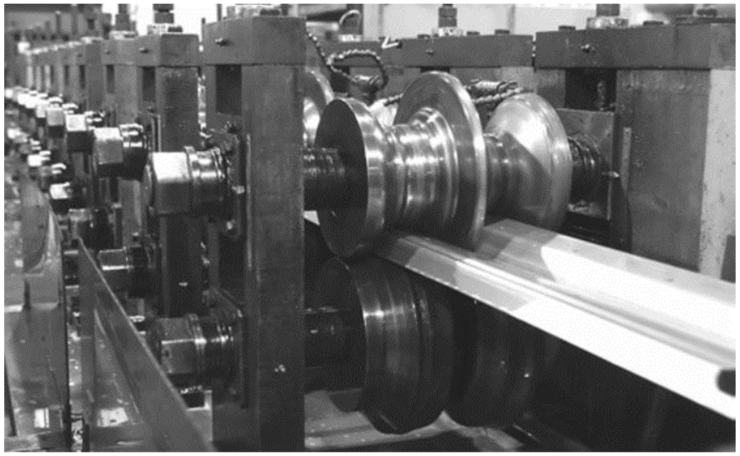
- Alternatively to slandered sections it is possible to obtain welded sections with various standard cross section configurations; standard sections and plates or from welding different plates together.



Some typical built-up shapes and sections (a) made from standard shapes, (b) made from standard shapes and plates, (c)made from plates

Cold-formed Steel

- Cold-formed steel sections is made from thin steel sheets usually 0.4 mm to 3.0 mm thick by roll-forming. Where the sheets/ coils are slit into the required width and fed through a series of dies, to form the stud, joist, angle or other cold-formed member.



- Cold-formed steel is predominately manufactured from scrap steel using either electric arc or basic oxygen furnaces.

- Cold-formed steel is used for structural framing of floors, walls and roofs as well as interior partitions and exterior curtain wall applications.

Cold-formed Steel

- A wide variety of shapes and sections can be produced by cold-forming and manufacturers have developed a wide range of products to meet specific applications

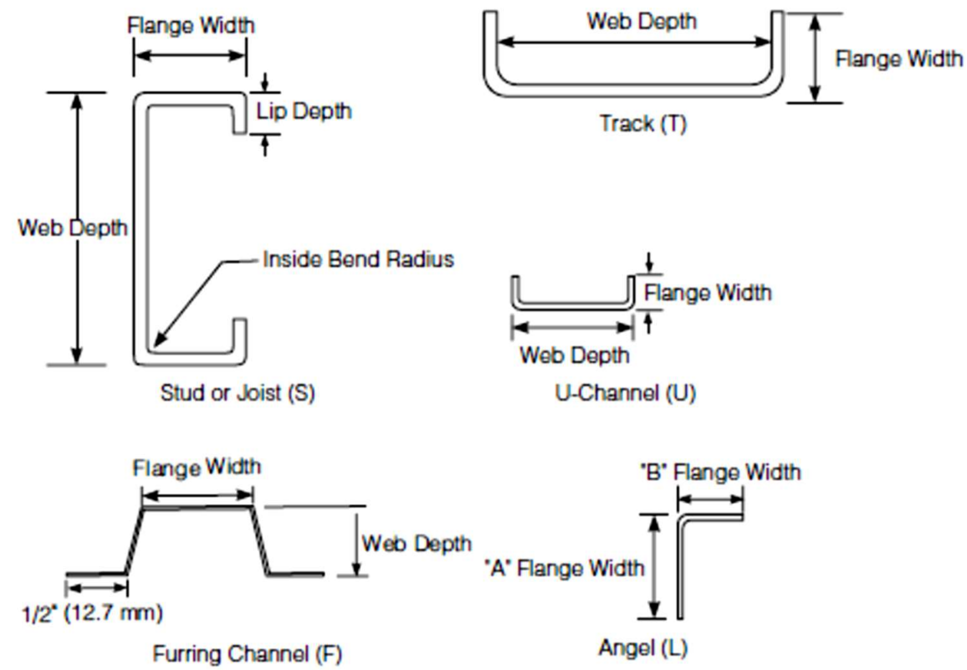


FIGURE 3.11 Generic cold-formed steel framing shapes.

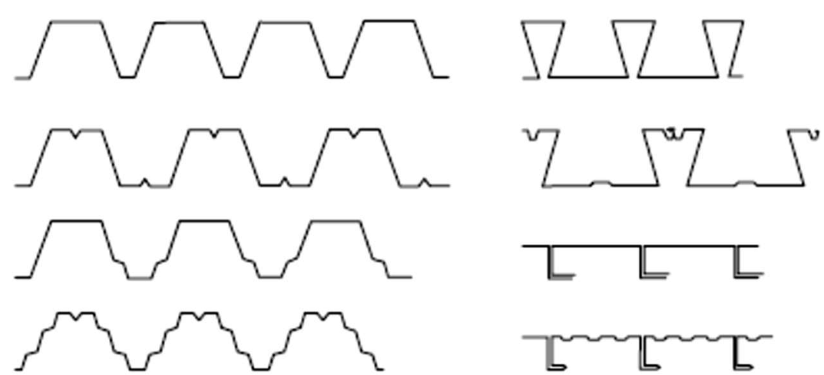


FIGURE 3.12 Common panel and deck shapes (TPU, 2009).

Reinforcing Steel

- Since concrete has negligible tensile strength, structural concrete members subjected to tensile and flexural stresses must be reinforced. Reinforcing steel (rebar) is manufactured in three forms:
  - Plain bars; provide only limited bond with the concrete
  - Deformed bars, have protrusions (deformations) at the surface; thus, they ensure a good bond between the bar and the concrete allowing the concrete and steel to work as one unit. Used in concrete beams, slabs, columns, walls, footings, pavements, and other concrete structures.

Reinforcing Steel

- Plain and Deformed bars Wire fabrics are flat sheets in which wires pass each other at right angles and specific spacing. Wire fabrics develop the anchorage in concrete at the welded intersections or through deformations of the bars. Usually used in some concrete slabs and pavements, mostly to resist temperature and shrinkage stresses.

Reinforcing Steel

- **Steel Type , Grades and available sizes of reinforcement bars**

Bars are made of four types of steel: A615 (billet), A616 (rail), A617 (axle), and A706 (low alloy) produced in three different grades (strength) as shown in the Table. The Billet steel is the most widely used steel in manufacturing of the reinforcement bars.

Types and Properties of Reinforcing Bars According to ASTM

ASTM Steel	Type	Grade US	Grade Metric	Tensile Strength Min., MPa (ksi)	Yield Strength* Min., MPa (ksi)
A615	Billet steel bars (plain and deformed)	40 60 75	280 420 520	483 (70) 620 (90) 689 (100)	276 (40) 414 (60) 517 (75)
A616	Rail steel (plain and deformed)	60	420	620 (90)	474 (60)
A617	Axle steel (plain and deformed)	40 60	280 420	483 (70) 620 (90)	276 (40) 414 (60)
A706	Low-alloy steel (deformed Bars)	60	420	552 (80)	414–538 (60–78)

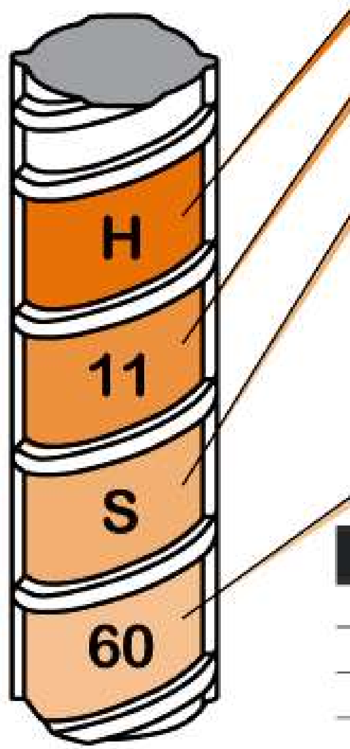
Available sizes in the local market

Diameter(mm)	Section area(mm2)	Weight(kg/m)
6	28.27	0.222
8	50.27	0.395
10	78.54	0.617
12	113.1	0.888
14	153.9	1.21
16	201.1	1.58
18	254.5	2.00
20	314.2	2.47
22	380.1	2.98
25	490.9	3.85
28	615.8	4.83
32	804.2	6.31
36	1018	7.99
40	1257	9.87
50	1964	15.42

Reinforcing Steel

- **Identification of the different bar types in the field**

Usually there are four marking symbols rolled into the bars as they are being produced. The symbols provide information about the reinforcing bar that can be read as shown in the figure.



Point of Origin
Letter(s) or symbol(s) of producing mill

Size Designation
3, 4, 5, 6, 7, 8, 9, 10, 11, 14, 18
[10, 13, 16, 19, 22, 25, 29, 32, 36, 42, 57]

Type of Steel
S = Carbon-Steel (A615/A615M)
W = Low-Alloy Steel (A706/A706M)
SS = Stainless-Steel (A955/A955M)
R = Rail-Steel (A996/A996M)
⌶ = Rail-Steel (A996/A996M)
A = Axle-Steel (A996/A996M)
CS = Low-Carbon Chromium (A1035/A1035M)

Minimum Yield Designation (Grade Mark or Grade Line)

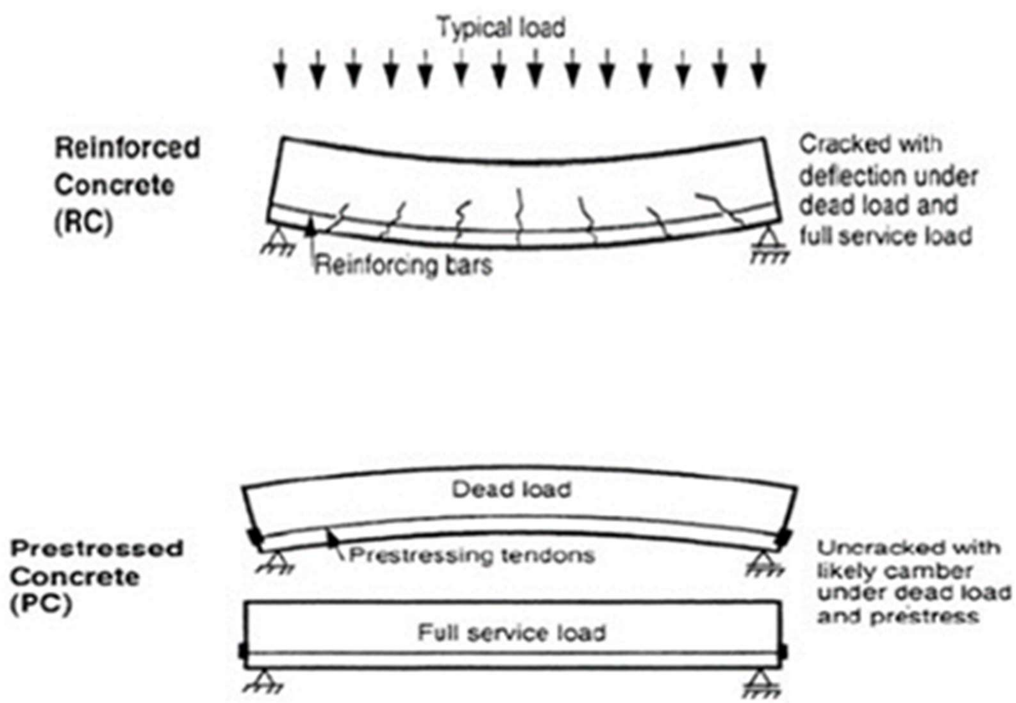
Inch-Pound Markings		Metric Markings	
60	Grade 60*	4	Grade 420*
75	Grade 75**	5	Grade 520**
80	Grade 80***	6	Grade 550***
100	Grade 100***	6	Grade 690***
120	Grade 120****	8	Grade 830****
None	Grade 40 or 50	None	Grade 280 or 350

*Or 1 Grade Line / **Or 2 Grade Lines / ***Or 3 Grade Lines / ****Or 4 Grade Lines

For stainless-steel (ASTM A955/A955M) reinforcing bars:
"•" for Grade 60 [420], "••" for Grade 75 [520]

Pre-stressed reinforcement

- Pre-stressed concrete is a form of concrete used in construction which is "pre-stressed" by being placed under compression prior to supporting any loads beyond its own dead weight. Pre-stressing removes a number of design limitations conventional concrete faces on span and load and also permits the building of roofs, floors, bridges, and walls with longer unsupported spans.



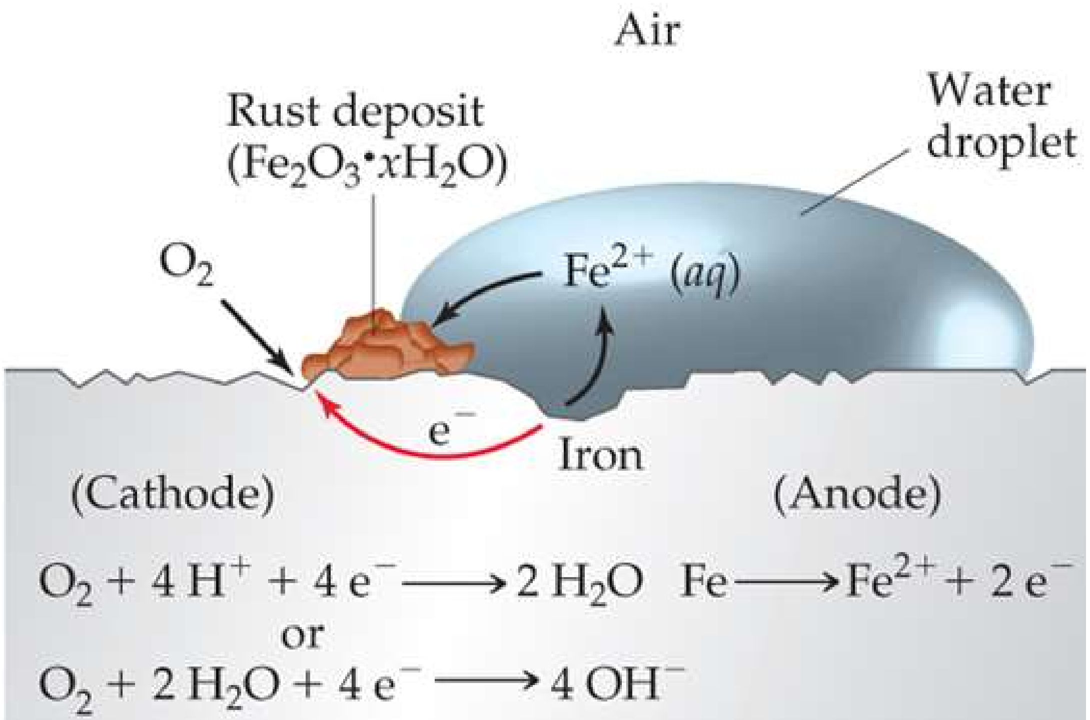
Pre-stressed reinforcement

- Pre-stressed reinforcement is the wires or tendons that are used to provide the pre-stressing force. Accordingly they will be under continuous tension. Thus, any stress relaxation will reduce the effectiveness of the reinforcement.

- Hence, Steel for pre-stressed concrete reinforcement must have high strength and low relaxation properties. High-carbon steels and high-strength alloy steels are used for this purpose.

Steel Corrosion

- Steel corrosion can be defined as deterioration due to electrochemical reactions with the metal and its environment. It can cause serious problems and /or dangerous failures.
- Steel corrosion or rusting occurs when the iron in the metal oxidizes. In order for corrosion to occur, both oxygen and water must be present.

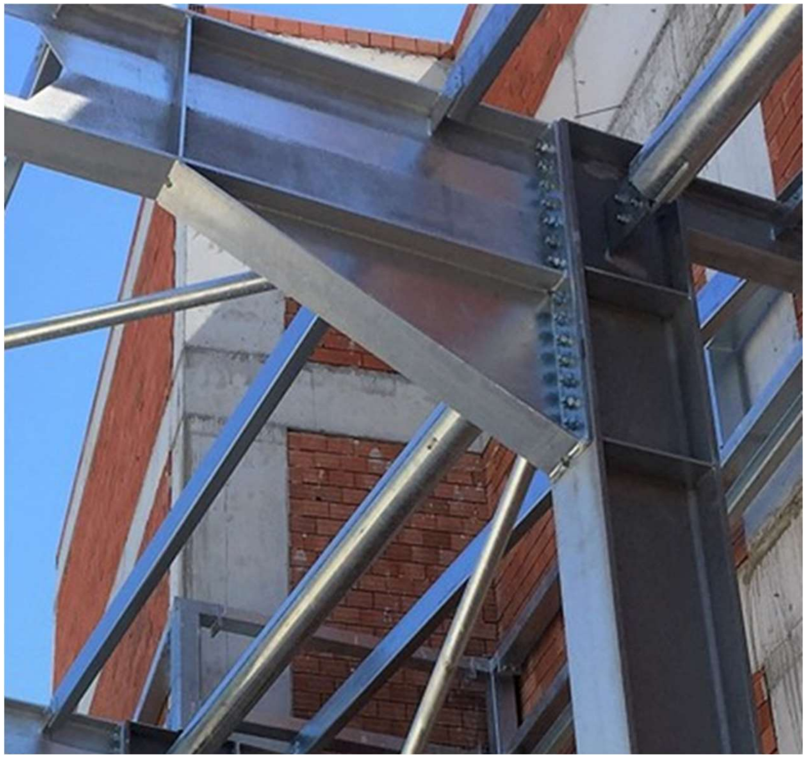


Methods for Corrosion Resistance

- **protective coating**
  - Barrier coatings work solely by isolating the steel from the moisture. These coatings have low water and oxygen permeability.

Methods for Corrosion Resistance

- Inhibitive primer coatings contain passivating pigments. They are low-solubility pigments that migrate to the steel surface when moisture passes through the film to passivate the steel surface.
- Sacrificial primers (cathodic protection) contain pigments such as elemental zinc.



Mechanical Testing

Tension Test

- The tension test (ASTM E8) on steel is performed to determine the yield strength, yield point, ultimate (tensile) strength, elongation, and reduction of area. Typically, the test is performed at temperatures between 10°C and 35°C.

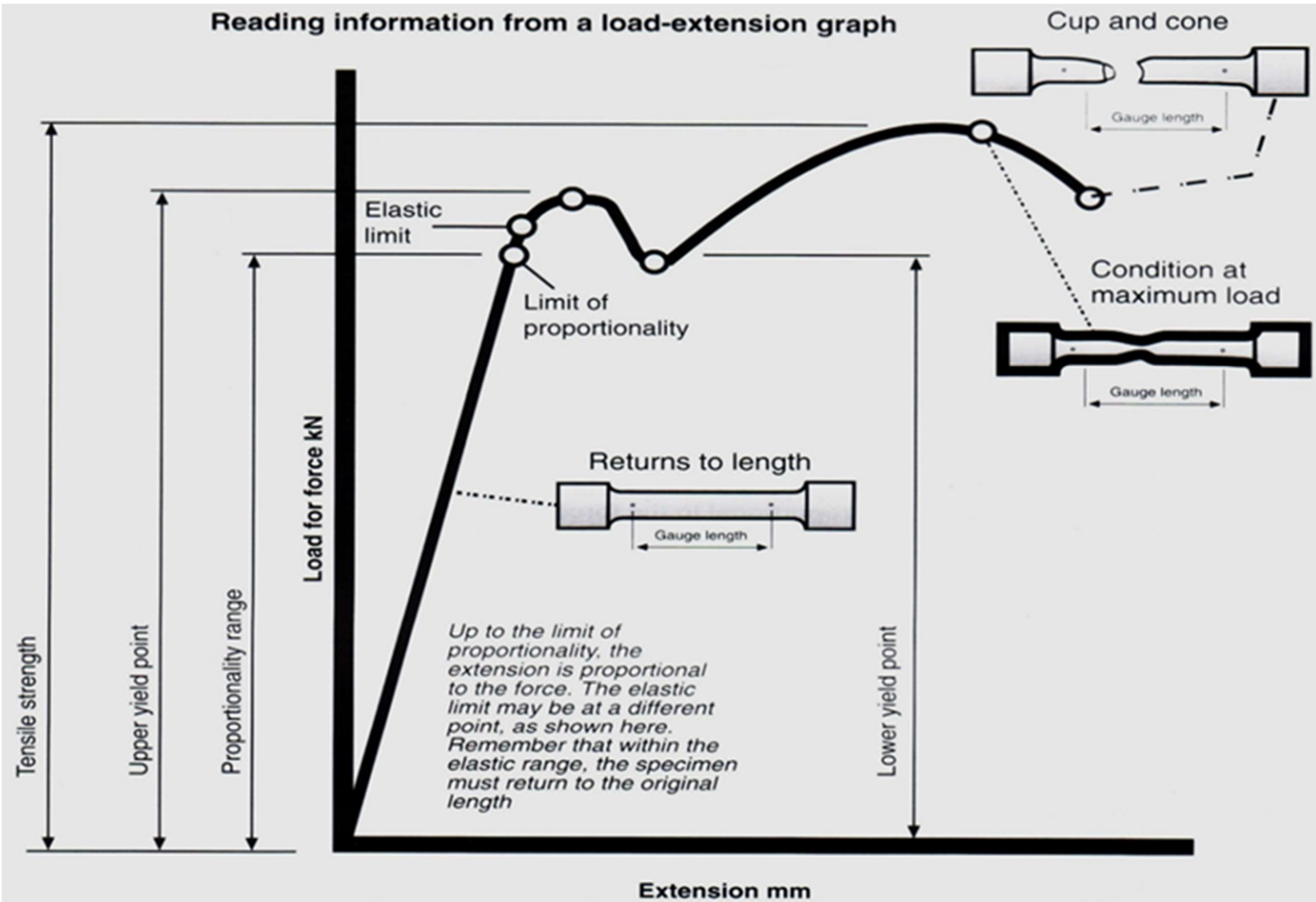
- Specimen. The test specimen can be either full sized or machined into a shape, as prescribed in the product specifications for the material being tested. It is desirable to use a small cross-sectional area at the center portion of the specimen to ensure fracture within the gauge length. The gauge length over which the elongation is measured typically is four times the diameter for most round-rod specimens.

Tension Test

- **Method**. A test specimen is fixed in the testing machine so that the axis of the specimen is placed at the center of the machine head to ensure axial tensile stresses within the gauge length without bending. Then axial load is applied to the specimen at a specified rate while the deformation of the entire gauge length is measured.

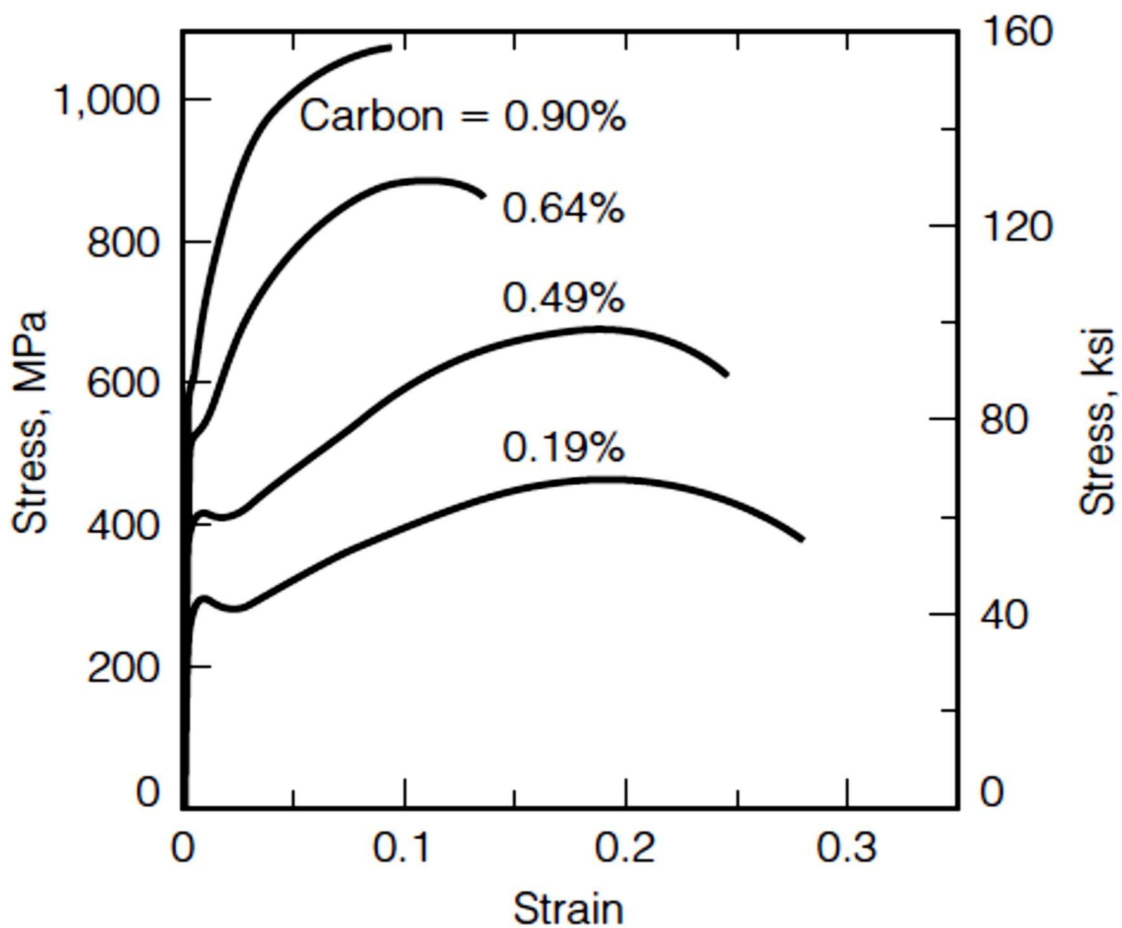
Tension Test

- **Stress – strain curve:** Mild steel has a unique stress–strain relation as shown below.



Tension Test

- Different carbon-content steels have different stress–strain relations. Increasing the carbon content in the steel increases the yield stress and reduces the ductility. However the increase in carbon content does not change the modulus of elasticity.



Hardness Test

- Hardness is a measure of a material's resistance to localized plastic deformation, such as a small dent or scratch on the surface of the material.
- A certain hardness is required for many machine parts and tools.
- Several tests are available to evaluate the hardness of materials. In these tests an indenter (penetrator) is forced into the surface of the material with a specified load magnitude and rate of application. The depth, or the size, of the indentation is measured and related to a hardness index number.

The Rockwell hardness test

- In this test, the depth of penetration of a diamond cone, or a steel ball, into the specimen is determined under fixed conditions.
- First, a preliminary load of 10 kg is applied, followed by an additional load. The Rockwell number, which is proportional to the difference in penetration between the preliminary and total loads, is read from the machine by means of a dial, digital display, pointer, or other device.

The Rockwell hardness test

- Two scales are frequently used, namely, B and C. Scale B uses a 1.588 mm steel ball indenter and a total load of 100 kg, while scale C uses a diamond spheroconical indenter with a 120° angle and a total load of 150 kg.
- The Rockwell hardness number is reported as a number, followed by the symbol HR, and another symbol representing the indenter used. For example, 68 HRC indicates a Rockwell hardness number of 68 on Rockwell C scale.
- **Test Advantages.** Hardness tests are simple, inexpensive, nondestructive, and do not require special specimens. Additionally other mechanical properties, such as the tensile strength, can be estimated from the hardness numbers. Therefore, hardness tests are very common and are typically performed more frequently than other mechanical tests.