CHAPTER 3

Steel
Introduction – Steel

3rd most used construction material after concrete and asphalt

- Iron ore → 1500 B.C. primitive furnace: iron
  → 18\textsuperscript{th} century blast furnace: mass iron production
  → mid-1800s Bessemer converter: steel

**Difference:**

- Concrete & asphalt
  - Engineers and contractors directly influence strength, stability, & durability

- Steel
  - Civil engineer has less flexibility in specifying steel
Construction Uses of Steel

• **Structural steel** → plates, bars, pipes, structural shapes, etc.
• **Cold formed steel** → studs, trusts, roofing, cladding
• **Fastening products** → bolts, nuts, washers
• **Reinforcing steel** → rebar for concrete
• **Miscellaneous** → forms, pans, hardware, etc.
Ferrous vs non-ferrous

Metals may be classified according to their iron content.

Ferrous metals → major constituent is iron
Non-ferrous metals → no or minor iron

The word ferrous is derived from the Latin term Ferrum which means containing iron.

Iron is one of the most abundant metallic material in earth’s crust (~4 to 5%).
Ferrous Metals

Ferrous metals are those metals the chief constituent of which is iron:

- pig iron,
- cast iron,
- steel.
IRON

Iron is extracted from iron ores such as

- **Hematite** ($Fe_2O_3$),
- **Magnetite** ($Fe_3O_4$),
- **Siderite** ($FeCO_3$),
- **Limonite** ($Fe_2O_3 \cdot nH_2O$).

Commercial iron ores contain 25-70% metallic iron.

Sulfur, phosphorous, silica and clay are main impurities.
Production of Iron

Iron ores, coke and limestone are heated together to high temperature for the extraction process of iron in a blast furnace.

Extraction is made by removing oxygen from the iron oxide of the ore and by removing a great part of the impurities found in the ore.

The metallic product thus obtained is called pig iron.

Pig iron is further refined to produce cast iron and steel.
**Blast Furnace**

The furnace is fed from the top. The iron ore (60%), coke (25%) and limestone (15%) are placed in alternate layers.

The oxygen of hot air blast causes the coke to burn.
In the blast furnace:

Coke provides the heat & supplies carbon (C) to extract iron.

Limestone acts as a flux that holds the impurities of ore and coke.
Steel Production Stages

1. Reduction of iron ore to pig iron (high carbon)
2. Refining pig iron to steel
3. Forming steel into products
Basic Reactions in Blast Furnace

C + O₂ → CO₂
CO₂ + C → 2CO
3CO + Fe₂O₃ → 2Fe + 3CO₂

The molten iron (@1600°C) collects at the bottom of the blast furnace.

The limestone introduced into the furnace first decomposes to CaO and CO₂ @~900°C. Then, the CaO reacts with, silica, alumina, sulfur, phosphorus and other ore impurities to form a molten slag. Slag collects on top of molten iron. Slag is a waste product of blast furnace.
Final Products of Blast Furnace Slag?

- Pig iron (raw iron) contains many dissolved impurities and also a high amount (3.5-4%) of carbon absorbed by the molten iron. **High C content makes the metal brittle.** Thus, it cannot be shaped easily.
- Slag is usually cooled very rapidly to obtain a granular amorphous material; which when ground, is an excellent admixture for concrete.
- Intergrinding the blast furnace slag with portland cement clinker produces blast-furnace slag cements.
Blast Furnace Slag?
Pig Iron

- Pig iron is found to be combined with carbon, silicon, manganese, sulphur and phosphorus.
- The characteristics of pig iron are chiefly determined by the carbon content it possesses.
- Not malleable at any temperature

Malleability: is the ability to be forged into desired shapes
What is Cast Iron?

- **Cast iron** is produced by remelting pig iron either in special furnaces to eliminate some impurities and to obtain more uniformity. The molten iron is finally cast into forms of desired shape.

- Depending on the pig iron used, the final carbon content of cast iron varies between 1.5-4%.
Cast Iron Examples

A cast iron pan.

Cast iron drain, waste and vent piping.
Reduction of Iron Ore to Pig Iron

Blast furnace with carbon (coal or coke) & limestone

- Limestone removes impurities from iron ore
- Slag (molten rock & impurities) is skimmed off the top
- Molten iron is collected at the bottom
Refining Pig Iron and Scrap to Steel

Remove excess carbon and other impurities by oxidation in another furnace

- **Basic oxygen furnace** – 300 tons in 25 minutes
- **Electric arc** – electric arc melts steel – lots of energy

• Deoxidize with aluminum, ferrosilicon, manganese, etc.

• **Killed Steel**: completely deoxidized
Forming Steel into Products

• Cast into ingots (large blocks that must be re-melted and re-shaped)
• Continuous shapes
**Iron-Carbon Phase Diagram**

Steel is an alloy of iron and carbon

- Higher carbon: steel is harder & more brittle
- Modulus of Elasticity is the same for all three (same atomic bonds)
  - Cast iron: high (>2%) carbon = brittle
  - High carbon steel: medium (0.8%-2%) carbon = brittle
  - Structural steel: low (0.15%-0.27%) carbon = ductile
Iron-Carbon Phase Diagram
**Cementite, Ferrite, Pearlite**

**Cementite** is a compound of iron and carbon found in high carbon steels, it is very hard and brittle.

**Ferrite** is the excess iron in low carbon steels, and gives the steel softness, enables it to be cold worked.

**Pearlite** is a mixture of ferrite and cementite, it is harder and less ductile than ferrite, but is softer and less brittle than cementite.

**Austenite.** Austenite is a metallic, non-magnetic solid solution of carbon and iron that exists in steel above the critical temperature of 1333°F (723°C).
Fe₃C is 6.7% carbon by weight. This corresponds to 100% Fe₃C carbide or cementite.
Three phases of solid iron
\[ \delta = \text{high temperature ferrite, FCC no practical significance to CE} \]
\[ \gamma = \text{austenite, BCC} \]
\[ \alpha = \text{low temperature ferrite, FCC} \]

\[ \gamma = \text{austenite, BCC has a lower atomic packing factor than FCC. The extra space in the lattice structure allows carbon in solution as an interstitial element.} \]

Hypoeutectoid alloys

Eutectoid material – pearlite
\[ \alpha \text{ ferrite percent carbon} = 0.022 \]
\[ \text{Fe}_3\text{C (iron carbide or cementite) 6.7}\% \text{ C} \]
Forms in thin plates – lamellae structure
Solid austenite with carbon in solution grains of uniform material

Proeutoid ferrite formed, accumulates at grain boundaries of austenite

$\alpha$ ferrite percent carbon = 0.022
austenite 0.77% carbon

Austenite transforms into pearlite

Grains of pearlite surrounded by skeleton of $\alpha$ ferrite
Determine amounts and compositions of phases and constituents of steel composed of 0.25% carbon just above and below the eutectoid isotherm.

%C of α = 0.022
%C of cementite = 6.67
%C of steel = 0.25

Using lever rule

\[
\%\alpha = \frac{[6.67 - 0.25]}{[6.67 - 0.22]} \times 100 = 96.6\%
\]

\[
\%\text{pearlite} = \frac{[0.25 - 0.022]}{[6.67 - 0.22]} \times 100 = 3.4\%
\]
Significance of ferrite, pearlite and iron carbide

• Ferrite has relatively low strength but is very ductile.
• Iron carbide has high strength but no ductility.
• Combining these two materials in different portions alters the mechanical properties of steel.

• Increasing the carbon content increases the strength and hardness but reduces ductility!

• Modulus of elasticity of steel does not change by altering the carbon content!
Heat Treatment

Refines grain structure, removes internal stresses, removes gases, changes electrical and magnetic properties

- **Types**
  - a) Annealing
  - b) Normalizing
  - c) Hardening
  - d) Tempering
Annealing

- Heating, then slowly cooling to room temperature.
- Steel gets softer & more ductile, increasing toughness.
Normalizing

- Similar to annealing, but hotter & air cooled
- Gives a uniform, fine-grained structure
- Provides high fracture toughness
- More corrective rather than strengthening or hardening
Hardening

- Higher heat, then rapid cooling by quenching in water/brine/oil
- Steel is harder & more brittle & must be followed by tempering.
Tempering

- Reheating hardened steel to a lower temperature and quenching
- Increases ductility and toughness after hardening – both effects
Temperatures for Heat Treating

Structural Steel Area of Interest
Steel Alloys

- 250,000 steel alloys
- ~200 used in engineering

• Steel alloy is steel + alloying metal to change properties
  - hardenability
  - corrosion resistance
  - machineability
  - ductility
  - strength

• Construction steels are low and medium carbon plain steels.

• Stainless steel for highly corrosive uses
  - add chromium, nickel, etc.
### Alloying Elements

<table>
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<th></th>
<th>Typical Ranges in Alloy Steels (%)</th>
<th>Principal Effects</th>
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<tbody>
<tr>
<td>Aluminum</td>
<td>&lt;2</td>
<td>Aids nitriding&lt;br&gt;Restricts grain froth&lt;br&gt;Removes oxygen in steel melting</td>
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<td>Sulfur</td>
<td>&lt;0.5</td>
<td>Adds machinability&lt;br&gt;Reduces weldability and ductility</td>
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<td>Chromium</td>
<td>0.3 to 0.4</td>
<td>Increases resistance to corrosion and oxidation&lt;br&gt;Increases hardenability&lt;br&gt;Increases high-temperature strength&lt;br&gt;Can combine with carbon to form hard, wear-resistant microconstituents</td>
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<td>Nickel</td>
<td>0.3 to 5</td>
<td>Promotes an austenitic structure&lt;br&gt;Increases hardenability&lt;br&gt;Increases toughness</td>
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<td>Copper</td>
<td>0.2 to 0.5</td>
<td>Promotes tenacious oxide film to aid atmospheric corrosion resistance</td>
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<td>Manganese</td>
<td>0.3 to 2</td>
<td>Increases hardenability&lt;br&gt;Promotes an austenitic structure&lt;br&gt;Combines with sulfur to reduce its adverse effects</td>
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<td>Silicon</td>
<td>0.2 to 2.5</td>
<td>Removes oxygen in steel making&lt;br&gt;Improves toughness&lt;br&gt;Increases hardenability</td>
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<tr>
<td>Molybdenum</td>
<td>0.1 to 0.5</td>
<td>Promotes grain refinement&lt;br&gt;Increases hardenability&lt;br&gt;Improves high-temperature strength</td>
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<tr>
<td>Vanadium</td>
<td>0.1 to 0.3</td>
<td>Promotes grain refinement Increases hardenability&lt;br&gt;Will combine with carbon to form wear-resistant microconstituents</td>
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</table>
Structural Steel

- Hot rolled structural shapes
- Cold formed cladding
Structural Steel

• Hot rolled structural shapes, plates, and bars used in columns, beams, brackets, frames, bridge girders, etc.

• Grades determined:
  ➢ Mechanical properties
    • Yield strength
    • Tensile or ultimate strength
    • Percent elongation
  ➢ Chemical composition
    • Percent carbon
    • Other requirements – limit undesirable chemicals, provide desired properties

• Types used for structural applications
  ➢ Carbon
  ➢ High-strength low-alloy
  ➢ Corrosion resistant high-strength low-alloy
<table>
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<tr>
<th>Steel Type</th>
<th>ASTM Designation</th>
<th>F_y^1 (ksi)</th>
<th>F_u^1 (ksi)</th>
<th>Minimum Elongation^2 (%)</th>
<th>C</th>
<th>Cu^5</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
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</table>

^1Minimum values unless range or other control noted

^2Two inch gauge length

^3Maximum values unless range or other control noted

^4A maximum yield to tensile strength ratio of 0.85 and carbon equivalent formula are included as mandatory in ASTM A992

^5Several steel specifications can include a minimum copper content to provide weather resistance

^6Range for plate given in table, bar range 0.6–0.9
# Mechanical Requirements for “Carbon” Steel

<table>
<thead>
<tr>
<th>ASTM designation</th>
<th>F&lt;br&gt;&lt;sub&gt;y&lt;br&gt;&lt;/sub&gt;&lt;sup&gt;1&lt;/sup&gt; (ksi)</th>
<th>F&lt;br&gt;&lt;sub&gt;u&lt;br&gt;&lt;/sub&gt;&lt;sup&gt;1&lt;/sup&gt; (ksi)</th>
<th>Elongation&lt;br&gt;&lt;sup&gt;2&lt;/sup&gt; (%)</th>
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1ksi=6,89 MPa
### Example Chemical Specifications for Carbon Steel

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<th>ASTM designation</th>
<th>Typical Chemical Composition[^3]</th>
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[^3]: Other elements controlled include nitrogen, chromium, silicon, molybdenum, and vanadium.
Section Shapes

(a) Wide flange
   - W A992
   - HP A572 G50
   - M A36

(b) I beam
   - S A36

(c) Channel
   - C, MC A36

Equal leg angle
   - L A36

Unequal leg angle
   - L A36

Tee

Sheet piling

Rail
Grade Selection Based on Shape

<table>
<thead>
<tr>
<th>Shape/Section</th>
<th>Preferred ASTM Material Standard</th>
<th>Other Applicable ASTM Material Standards</th>
</tr>
</thead>
</table>
| W             | A992                             | A242 Grade 42<sup>c</sup>, 46<sup>b</sup>, 50<sup>a</sup>  
|               |                                  | A529 Grade 50<sup>a</sup>, 55<sup>c</sup>  
|               |                                  | A572 Grade 42, 50, 55, 60<sup>c</sup>, 65<sup>c</sup>  
|               |                                  | A588 Grade 50  
|               |                                  | A913 Grade 50, 60, 65, 70  
| HP            | A572 Grade 50                    | A36 Grade 36  
|               |                                  | A242 Grade 46<sup>b</sup>, 50<sup>a</sup>  
|               |                                  | A529 Grade 50<sup>a</sup>, 55<sup>c</sup>  
|               |                                  | A572 Grade 42, 55, 60<sup>c</sup>, 65<sup>c</sup>  
|               |                                  | A588 Grade 50  
|               |                                  | A913 Grade 50, 60, 65, 70  
|               |                                  | A992 – confirmation required  
| M, S, C, MC   | A36                              | A242 Grade 50<sup>a</sup>  
|               |                                  | A529 Grade 50<sup>a</sup>, 55<sup>c</sup>  
|               |                                  | A572 Grade 42, 50, 55, 60<sup>c</sup>, 65<sup>c</sup>  
|               |                                  | A588 Grade 50  
|               |                                  | A913 Grade 50, 60, 65, 70  
|               |                                  | A992 – confirmation required  
| L             | A36                              | A242 Grade 46<sup>b</sup>, 50<sup>a</sup>  
|               |                                  | A529 Grade 50<sup>a</sup>, 55<sup>c</sup>  
|               |                                  | A572 Grade 42, 50, 55, 60<sup>c</sup>, 65<sup>c</sup>  
|               |                                  | A588 Grade 50  
|               |                                  | A913 Grade 50, 60, 65, 70  
|               |                                  | A992 – confirmation required  
| HSS           | A500 Grade B                      | A500 Grade C  
|               |                                  | A501 Grade 36  
|               |                                  | A618 Grade I, II and III  
|               |                                  | A847 Grade 50  
| Pipe          | A53 Grade B                       | N/A  

Hollow structural section either circular or rectangular
Specialty Steels

• High performance steels

• Stainless steel has minimum 10% chromium (common steels have 0.3% – 0.4%).
Cold Formed Steel

• Grades

  ➢ Multiple grades are acceptable.

  ➢ Steel Stud Manufactures Association recognizes two yield stress grades, 33 and 55 ksi.

• Cold forming results in plastic deformation causing strain-hardening that increases the yield strength, tensile (ultimate) strength and hardness, but reduces ductility.

• Cold forming increases tensile strength by 50-70% and ultimate strength by 20-30%.
Stages of Cold Forming

1. Flat
2. 3. 4.
5. 6.

Finished section
Cold Formed Steel Shapes

• Structural design requires special considerations due to
  ➢ buckling
  ➢ corrosion
Fastening Products

- Conventional bolts
- Twist-off-type tension control bolt assemblies
- Nuts
- Washers
- Compressible-washer-type direct tension indicators
- Anchor rods
- Threaded rods
- Forged steel structural hardware
Reinforcing Steel
Reinforcing Steel

• Conventional Reinforcing Steel
  ➢ Plain bars, deformed bars, and plain and deformed wire fabrics

• Bars are made of 4 types of steel: A615 (billet), A616 (rail), A617 (axle), and A706 (low-alloy)

• Steel for Prestressed Concrete
  ➢ Requires special wires, strands, cables, and bars
  ➢ Must have high strength and low relaxation properties
  ➢ Made of high-carbon steels and high-strength alloy steels
Steel Bars For Concrete Reinforcement

Concrete → to resist compressive stresses
Steel Bar → to resist tensile stresses therefore used in tension zones.

- Plain Bars: smooth surfaces
- Deformed Bars: to increase the bond characteristics they have some deformation on the surfaces
- Wire Mesh: Welded at joints & used in slabs.
Specifications for Reinforcements

The requirements for reinforcements are cited in

- TS 708 Steel Bars for Concrete
- TS 500 Building Code Requirements for Reinforced Concrete
- ASTM A 615

TS 708 $\rightarrow$ C should be $<0.25\%$ $\rightarrow$ plain
$<0.4\%$ $\rightarrow$ def
TS 708
Nisan 2010

ICS 77.140.60

ÇELİK - BETONARME İÇİN - DONATI ÇELİĞİ
Steel for the reinforcement of concrete - Reinforcing steel
# Steel Bars for Concrete According to TS 500 & TS 708

<table>
<thead>
<tr>
<th>Type</th>
<th>Flat Surface</th>
<th>Ribbed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>S220</td>
<td>S420</td>
</tr>
<tr>
<td></td>
<td>B420B</td>
<td>B420C</td>
</tr>
<tr>
<td></td>
<td>B500B</td>
<td>B500C</td>
</tr>
<tr>
<td>Category</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yield Strength Re (N/mm²)</td>
<td>220</td>
<td>420</td>
</tr>
<tr>
<td>Tensile Strength Rm (N/mm²)</td>
<td>340</td>
<td>500</td>
</tr>
<tr>
<td>Ratio of Tensile Strength / Yield Strength Rm/Re</td>
<td>min. 1,20</td>
<td>min. 1,15</td>
</tr>
<tr>
<td></td>
<td></td>
<td>min 1,08</td>
</tr>
<tr>
<td></td>
<td></td>
<td>≥1,15 ≤1,35</td>
</tr>
<tr>
<td></td>
<td></td>
<td>min. 1,08</td>
</tr>
<tr>
<td></td>
<td></td>
<td>≥1,15 ≤1,35</td>
</tr>
<tr>
<td>Ratio of Experimental Yield Strength / Characteristic Yield Strength React./Renom. (Max.)</td>
<td></td>
<td>1,30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1,30</td>
</tr>
<tr>
<td>Elongation at Rupture (min.) A₅ (%)</td>
<td>18</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>12</td>
</tr>
<tr>
<td></td>
<td></td>
<td>12</td>
</tr>
<tr>
<td>Total Elongation at Maximum Load(min.) Agt(%)</td>
<td></td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7,5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7,5</td>
</tr>
</tbody>
</table>

* Produced by hot rolling, ** Produced by cold working
### Table 3.9 Standard-Size Reinforcing Bars According to ASTM A615\(^*\)

<table>
<thead>
<tr>
<th>Bar Designation Number(^*)</th>
<th>Nominal Mass (kg/m)</th>
<th>Diameter (mm)</th>
<th>Cross-Sectional Area (mm(^2))</th>
<th>Perimeter (mm)</th>
<th>Maximum Average Spacing</th>
<th>Minimum Average Height</th>
<th>Maximum Gap ****</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 [3]</td>
<td>0.560</td>
<td>9.5</td>
<td>71</td>
<td>29.9</td>
<td>6.7</td>
<td>0.38</td>
<td>3.6</td>
</tr>
<tr>
<td>13 [4]</td>
<td>0.994</td>
<td>12.7</td>
<td>129</td>
<td>39.9</td>
<td>8.9</td>
<td>0.51</td>
<td>4.9</td>
</tr>
<tr>
<td>16 [5]</td>
<td>1.552</td>
<td>15.9</td>
<td>199</td>
<td>49.9</td>
<td>11.1</td>
<td>0.71</td>
<td>6.1</td>
</tr>
<tr>
<td>19 [6]</td>
<td>2.235</td>
<td>19.1</td>
<td>284</td>
<td>59.8</td>
<td>13.3</td>
<td>0.97</td>
<td>7.3</td>
</tr>
<tr>
<td>22 [7]</td>
<td>3.042</td>
<td>22.2</td>
<td>387</td>
<td>69.8</td>
<td>15.5</td>
<td>1.12</td>
<td>8.5</td>
</tr>
<tr>
<td>25 [8]</td>
<td>3.973</td>
<td>25.4</td>
<td>510</td>
<td>79.8</td>
<td>17.8</td>
<td>1.27</td>
<td>9.7</td>
</tr>
<tr>
<td>29 [9]</td>
<td>5.059</td>
<td>28.7</td>
<td>645</td>
<td>90.0</td>
<td>20.1</td>
<td>1.42</td>
<td>10.9</td>
</tr>
<tr>
<td>32 [10]</td>
<td>6.404</td>
<td>32.3</td>
<td>819</td>
<td>101.3</td>
<td>22.6</td>
<td>1.63</td>
<td>12.4</td>
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<tr>
<td>36 [11]</td>
<td>7.907</td>
<td>35.8</td>
<td>1006</td>
<td>112.5</td>
<td>25.1</td>
<td>1.80</td>
<td>13.7</td>
</tr>
<tr>
<td>43 [14]</td>
<td>11.38</td>
<td>43.0</td>
<td>1452</td>
<td>135.1</td>
<td>30.1</td>
<td>2.16</td>
<td>16.5</td>
</tr>
<tr>
<td>57 [18]</td>
<td>20.24</td>
<td>57.3</td>
<td>2581</td>
<td>180.1</td>
<td>40.1</td>
<td>2.59</td>
<td>21.9</td>
</tr>
</tbody>
</table>

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\(^*\)Bar numbers approximate the number of millimeters of the nominal diameter of the bars. [Bar numbers are based on the number of eighths of an inch of the nominal diameter of the bars.]

\(^*\)The nominal dimensions of a deformed bar are equivalent to those of a plain round bar having the same weight per meter as the deformed bar.

\(^*\)Requirements for protrusions on the surface of the bar.

\(^*\)Chord 12.5% of Nominal Perimeter
ASTM Reinforcing Bare Identification

- **MAIN RIBS**
- **LETTER or SYMBOL** for PRODUCING MILL
- **BAR SIZE**
- **TYPE of STEEL**
- **GRADE** (No Grade Marking Required)

**Example:**
- **GRADE 40 (300)**
- **GRADE 60 (420)**
Mechanical Testing of Steel

Tension Test

• Determine yield strength, ultimate (tensile) strength, elongation, and reduction of area (Poisson's Ratio)

• Plate, sheet, round rod, wire, and tube can be tested
  ➢ Typical specimens are round or rectangular
Testing Set Up

- Crosshead
- Fixed beam
- Threaded end
- Specimen
- Extensometer
Sample Loaded to Failure

Cup and cone failure

Neck area
Typical Stress-Strain Behavior of Mild Steel

- $\sigma-\varepsilon$ is linear elastic up to proportional limit.
- Then non-linear elastic up to elastic limit = yield point = strain increases at constant stress.
- Then plastic deformation until failure.
Effect of Carbon on Mechanical Behavior

Structural Steel

0.12 to 0.30
Figure 3.19 Example of effect of specimen orientation on measured tensile properties of steel.
Torsion Test

• Determine shear modulus, G,
  ➢ designing members under torsion,
    • rotating shafts
    • helical compression springs
  ➢ Applied torque and angle of twist are measured on a cylindrical or tubular specimen.
  ➢ \( \tau - \gamma \) is linear elastic up to the proportional limit

\[
G = \frac{\tau}{\gamma} \quad \text{very similar to } E = \frac{\sigma}{\varepsilon}
\]
Charpy V Notch Impact Test

- Measure toughness or fracture energy at different temperatures
- Specimen of rectangular cross-section with a V notch
- Charpy machine with a pendulum that breaks the specimen
  - By measuring the height of the swing arm after striking the specimen, the energy required to fracture is computed (higher head = less energy absorbed)
- Energy absorbed is high at high temp. (shear = ductile) and low at low temp. (cleavage = brittle)
**Loss of Toughness with Reduction in Temperature**

- Large area of brittle cleavage, low energy absorption
- Large shear area ductile failure, high energy absorption

![Graph showing toughness vs. temperature](image-url)
Bend Test

• Ability of steel or a weld to resist cracking during bending
• Steel is often bent to a desired shape, especially rebar
• Bend the specimen through a certain angle and to a certain inside radius
**Hardness Test**

• Measures resistance to small dents and scratches

• Need very high hardness for many machine parts & tools

• Spring-loaded indenter (hardened steel penetrating ball) is forced into the surface of the material with a specified load and rate.

• Depth or size of indentation is related to hardness number.
Welding

• Joining two metal pieces by applying heat
  ➢ partial melting fuses the pieces together
  ➢ distortion caused by uneven heating
• Arc Welding or “Stick Welding”
  ➢ Flux on the electrode (“stick”) shields the molten metal from atmosphere to prevent oxidation.
• Gas Welding or “MIG Welding”
  ➢ “Metal in Gas” uses shielding gas instead of flux.
Steel Corrosion

• Oxidation (rust) can cause serious weakening of structures.

• Cost of corrosion is about $8 billion per year in U.S. alone.

• Steel is made by using heat to separate oxygen and iron molecules in the ore – corrosion is a natural process.
Corrosion Protection Methods

- Active corrosion protection
- Passive corrosion protection
- Permanent corrosion protection
- Temporary corrosion protection
**Required for Corrosion**

1. **Anode**: Positive electrode where corrosion occurs
2. **Cathode**: Negative electrode needed for electric current
3. **Conductor**: Metallic pathway for electrons to flow between electrodes
4. **Electrolyte**: Liquid that can support the flow of electrons

- 1, 2, and 3 are present in steel.
- 4 is moisture (in air).
- Pure water is not a good electrolyte, contaminants on the steel or in the air provides electrolyte (salt, acid rain, etc.).
Corrosion Resistance

• Control rather than stop corrosion

• Protective coatings (paint, etc.) can be used to isolate the steel from moisture.

1. Barrier coatings
   ➢ Standard paint isolates steel from moisture & must be repeated.

2. Inhabitive primer coatings
   ➢ Pigments that migrate to the steel surface to passivate it (transfer electrons)

3. Sacrificial primers (cathodic protection)
   ➢ Metal pigments (zinc) become the anode, give up electrons to the steel, and corrode instead of the steel.
Cathodic Protection

- Protective current supplies electrons to the structure.
- The electrons cover the electron requirements for the reduction of oxygen which comes into contact with the metal surface.
- Without cathodic protection, the electrons cause decomposition of the metal.
- The potential of the metal surface is sufficiently reduced to prevent disassociation of positive ions from the metal.
- Where formerly an anodic reaction took place, the oxygen is reduced by cathodic reaction.
- The entire surface of the structure becomes a safe cathode, i.e., the metal is "cathodically " protected.