Steel (part 1)

Chapter 3†

† Mamlouk, M.S., and Zaniewski, J.P. (2006). ***Materials for Civil and Construction Engineers***, 2nd ed., Prentice Hall

What we are going to talk about …

- Introduction
- Iron
- Production of steel
- Phase diagrams
  - Iron-carbon phase diagram
- Carbon content
- Strengthening mechanisms
- Mechanical properties

Introduction

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

Iron

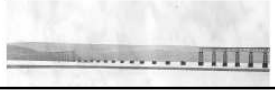
- Basic constituent of steel
  - Iron is widely available, but only in combination with other elements
- Found in the form of ores
  - Limonite – $Fe_2O_3 \cdot nH_2O$ (brown iron ore)
  - Hematite – Fe_2O_3 (red iron ore), most commonly used, contains about 70% of pure iron
  - Magnetite – Fe_3O_4

Iron Products: 3 commercial forms

- Wrought iron (Pipes and blacksmith work)
  - < 0.1% carbon by weight
  - contains small amount of slag (< 3%)
  - can be moulded easily
  - good corrosion resistance
- Steel
  - 0.1 – 2% carbon
- Cast iron (Hardware, Machine parts)
  - 5% carbon
  - strong, hard, brittle … some catastrophic failures

carbon content increases

Steel Products



Steel Products

- Structural Steel (continuous casting and hot-rolling). Ex. Columns
- Cold-formed steel. Ex. Trusses, decking
- Fastening products
- Reinforcing steel

Steel Products

- Civil Engineers rarely have the opportunity to formulate steel with specific properties
- Select existing products
- Even shapes are restricted to commonly available
- Exception: Bridges – plate steel

Production of steel

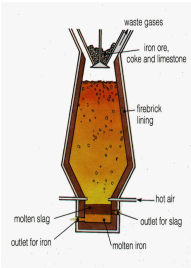
Three phases

- Reducing iron ore to pig iron
- Refining pig iron to steel
- Forming the steel into products

Production of steel

Material used to produce pig iron

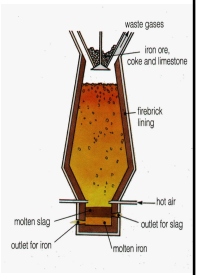
- Coal
  - Supplies carbon to reduce iron oxides in the ore
- Lime stone
  - Used to help remove impurities
- Iron ore



The processed ore contains 65% iron

Production of steel

- Iron ore → BLAST FURNACE = Pig iron
  - Principle function: reduce the iron ore and to eliminate impurities
  - T ~ 1600 °C
  - The "molten iron" is collected at the bottom
  - A non-metallic by-product (slag) floats on top of molten iron
    - Used as an admixture in concrete



Production of steel

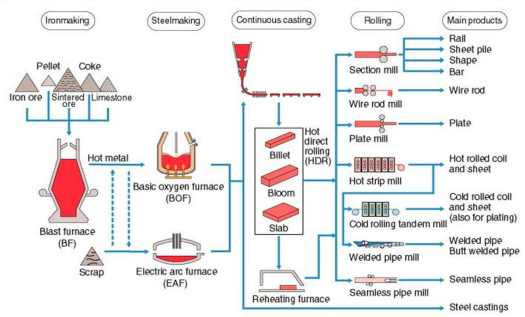
Molten iron+ Alloying agents → STEEL PRODUCTS

- Alloys are added to improve one or more of the following properties:
  - Resistance
  - Ductility
  - Corrosion resistance
  - Machinability

Production of steel

- The principal alloying element used are:
  - **Manganese**, which provides strength & toughness.
  - **Silicon** provides strength and hardening properties.
  - **Nickel and chromium** produce stainless steel.
  - **Copper** improves the corrosion resistance.

Summary



Steel Composition

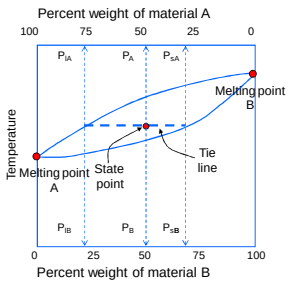
- Steel is basically an alloy of iron and carbon
- In plain carbon steels, the amounts of carbon & manganese are restricted, and other alloying elements are not normally included.
- The properties and behaviour of steel are highly influenced by:
  - **carbon content**
  - use of alloying elements
  - **rate of cooling**
  - subsequent heat treatments

Phase Diagrams

Also known as equilibrium diagram

- Phase: liquid & solid states of a material
- Phase diagram displays relationship between percent of elements & transition temperatures
- 3 types of Phase diagrams, for:
  - soluble materials,
  - Insoluble materials,
  - partially soluble materials

Phase Diagram soluble materials



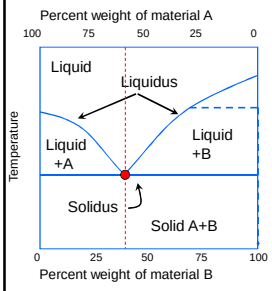
State point – combination of temperature and material composition

Tie line – horizontal line drawn through the state point

Vertical projection of the intersection of the tie line and liquidus identifies the percent of the liquid that is material A or B.

Similar for tie line-solidus vertical projection.

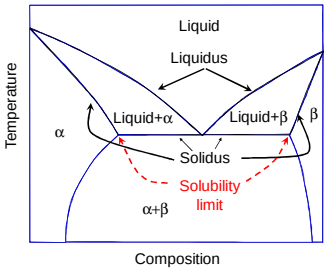
Phase Diagram insoluble materials



Projecting a tie line in the Liquid + B area shows that the solid material is composed of 100% B.

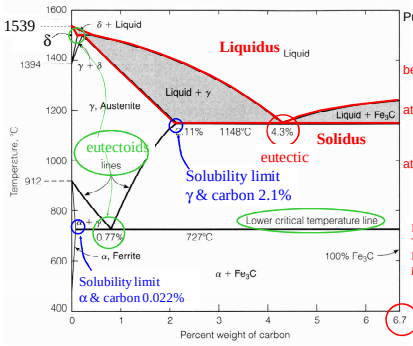
Eutectic – Sudden transition from liquid to solid without a two phase region.

Partially soluble materials



α and β are solid solutions of the A and B materials. The materials are partially soluble.

Steel – **Iron-Carbon** Phase Diagram



Pure iron goes through 2 transformations as temperature increases:

below 912°C has a body centred cubic (BCC) structure called ***ferrite***,

at 912°C ferrite undergoes change to a face-centred cubic (FCC) structure called ***austenite***,

at 1394°C another change to return a BCC structure

Fe_3C is 6.7% carbon by weight

This corresponds to 100% Fe_3C

iron carbide or cementite

Steel – **Iron-Carbon** Phase Diagram

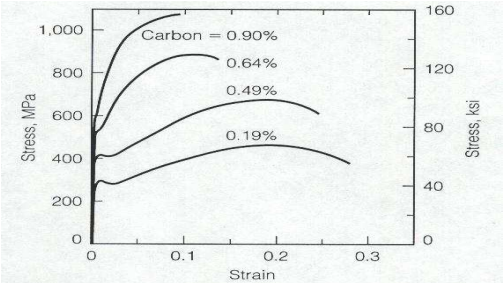
Importance ?

- Map of the changes in microstructure at the atomic level as a function of temperature
- The microstructure of steel is a function of compostion, temperature …
- Steel = Iron + Carbon
  - Amount of "C", impacts strength and ductility
  - Note max possible = 6.7% C = iron carbide
- The diagram also explains HEAT TREATMENT of steels

Effect of Carbon content

- As C ↑ the microstructure of steel is greatly affected
- Pure iron is soft and ductile
- Structural steel is in the region between 0–2% carbon. Beyond 2% carbon content, the material is not usable as structural steel.
- ↑ C: Increases Resistance but reduces Ductility
  - Cast Iron (C >2%) : Very brittle
  - High-Carbon steel (0.8-2%) : Less ductile
  - Low –Carbon steel (0.15-0.27%) : Ductile

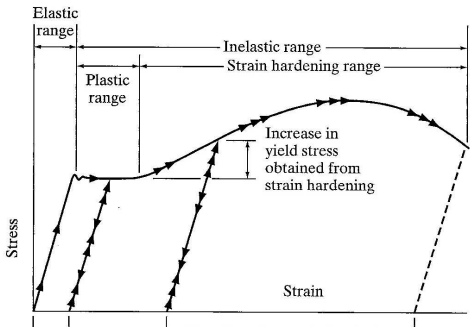
Effect of Carbon content



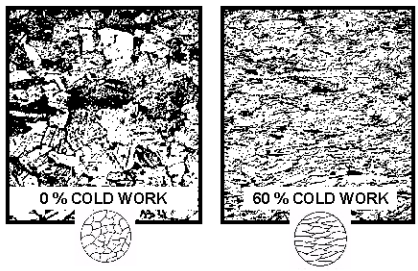
Strengthening Mechanisms

- Most structural steel section are formed from large casting by a series of rolling operations.
- Properties can be changed by subsequent heat treatment of the steel section.
  - **Work (strain) hardening**
  - **Heat treatments**
  - **Alloying**

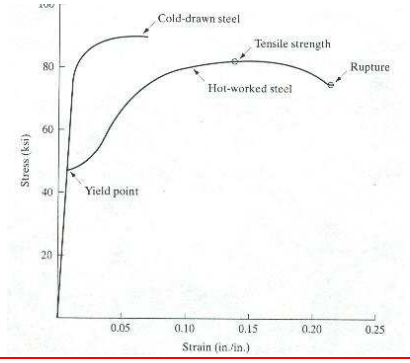
Work (Strain) Hardening



Work (Strain) Hardening



Work (Strain) Hardening



Heat Treatment

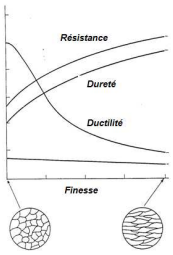
- Involves the heating and cooling of metals in the solid state
- Changes the mechanical properties so the metal can be more useful
- Metals can be made harder, stronger and more impact resistant **or** metals can be made softer and more ductile

Heat Treatment

- Hardness, toughness, strength, & ductility can be affected
- Types of heat treatment:
  - **ANNEALING**
  - **NORMALIZING**
  - **HARDENING**
  - **TEMPERING**

Cooling Rate

- Slow cooling → coarse grained steel
- Rapid cooling → fine grained steel
- Fine-grained materials
  - ✓ higher strengths
  - ✓ more uniform in structure
  - ✓ smoother surfaces



Steps for all heat treatments

- Heating
- Holding or “soaking”
- Cooling

Time and temperature are important at all 3 steps

Normalizing

- Produces a uniform, fine-grained microstructures.
- More of a corrective measure than strengthening.

Annealing

- Objective:
  - soften the steel,
  - remove internal stresses
  - Increase ductility and toughness
  - Heating metal & slowly cooling it to room temp. in furnace
  - Remove gases

Quenching (Hardening)

- Slowly heating metal + Quenched (cooled rapidly) by plunging into water, oil, or brine
- Hardens (strains) the steel , i.e., puts the steel in a state of strain.
- Must be followed by tempering

Tempering

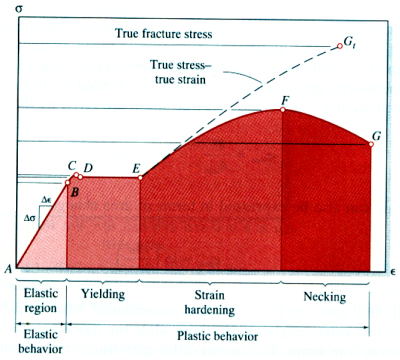
- Usually done after hardening (which results in undesirable brittleness) to improve ductility and toughness
- After Quenching, the steel is cooled to about 40 degrees and then reheated. The steel is maintained at elevated temp. for about two hours followed by air cooling
- Increases ductility & toughness of steel, but reduces strength & hardness

Heat treatment videos

http://www.youtube.com/watch?v=p3bkZBJV7X8&feature=related

http://www.youtube.com/watch?v=COasmrnxbqg&feature=related

Uniaxial Tensile Stress-Strain Curve



Construction uses of steel

- Rolled products – Rolled sections (beams, columns, trusses)
- Bars : Rebar in reinforced concrete
- Cold-formed steel: decking (floors, roofs)
- Assembly products: bolts, nuts, screws, etc.

Steel Classification : Grade

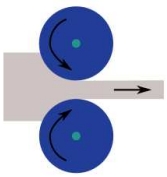
- Grade ⇨ based on Strength and Type
- Standard: CSA G40.21-M
  - chemical composition
  - strength level
  - methods of manufacture
- Each grade identified by a number and a letter
  - Number → yield point in MPa
  - Letter → characteristics of the 6 types of steel available
- For example, 350W → yield point of 350 MPa, weldable steel

Steel Grades

Type G	General construction steel	230, 350, 400
Type W	Weldable steel	260, 300, 350, 380, 400, 480
Type WT	Weldable notch tough steel	260, 300, 350, 380, 400, 480
Type R	Atmospheric corrosion-resistant steel	350
Type A	Atmospheric corrosion-resistant weldable steel	350, 400, 480
Type AT	Atmospheric corrosion-resistant weldable notch tough steel	350, 400, 480
Type Q	Quenched and tempered low alloy steel plate	700
Type QT	Quenched and tempered low alloy notch tough steel plate	700

Steel-Products (1) : Hot-rolled sections

- Sections are hot-rolled
- Applications: beams, columns, trusses in buildings and bridges



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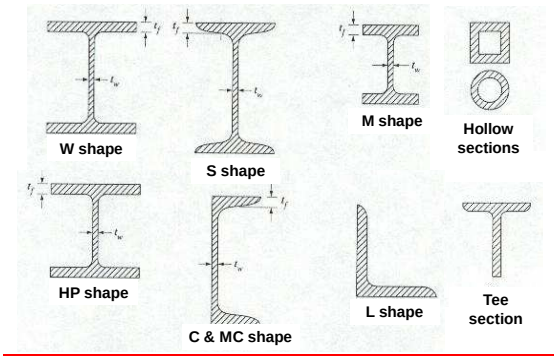


Steel-Products (1) : Hot-rolled sections

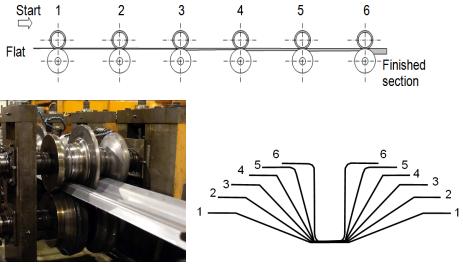
- Code / standard : CSA S16-09
- Handbook of steel construction

BEAM SELECTION TABLE
WWF and W Shapes

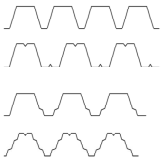
Designation	V_r	I_x	b	L_u	M_r	
	kN	10^6 mm^4	mm	mm	$\leq L_u$	2 000
W530x66	928	351	165	1 980	484	483
†W530x72	926	401	207	2 750	475	—
W410x74	821	275	180	2 470	469	—

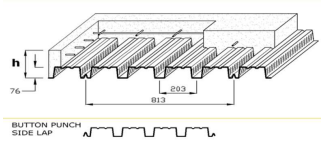
Steel Products (2) - Cold forming

- Work strain-hardening is used to increase resistance
- Example Applications: Roof and Composite floor decks



Steel Products (2) - Cold forming



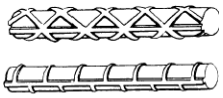


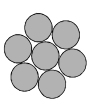
- Structural design requires special considerations due to
  - buckling
  - corrosion

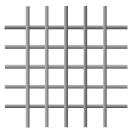
Steel Products (3) : Reinforcement

Reinforcement

- Plain & deformed bars
- Wire for welded wire fabric
- Bars, wires & strands for pre-stressing





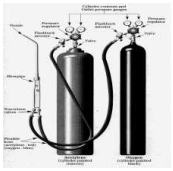


Standard Deformed Reinforcing Bars

Bar Designation	Nominal Dimensions			Mass per Unit Length kg/m
	Diameter mm	Area mm^2	Perimeter mm	
10	11.3	100	35.5	0.785
15	16.0	200	50.1	1.570
20	19.5	300	61.3	2.355
25	25.2	500	79.2	3.925
30	29.9	700	93.9	5.495
35	35.7	1000	112.2	7.850
45	43.7	1500	137.3	11.775
55	56.4	2500	177.2	19.625

Weldability

- Capacity of a metal to be joined by welding into a structure
  - Decreases as C & alloy content increases
  - Strong influence on fatigue strength
- Two types: Arc and Gaz welding



Corrosion

- Oxidation (rust) can cause serious weakening of structures.
- Cost of corrosion ($8 billion /year in U.S. alone)
  - Steel structures
  - Reinforced concrete structures

Required for corrossion

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 Mechanism

- Deterioration of a metal by electrochemical reaction with its environment
- Electrochemical process
  - Anode ⇨ oxidation of iron
    $2Fe \rightarrow 2Fe^{++} + 4e^{-}$
  - Cathode ⇨ reduction of oxygen
    $O_2 + 2H_2O + 4e^{-} \rightarrow 4OH^{-}$

RUST

$2Fe^{++} + 4OH^{-} \rightarrow 2Fe(OH)_2 \rightarrow \boxed{Fe_2O_3 \cdot nH_2O}$

Forms of Steel Corrosion

- General corrosion
  - ✓ uniform corrosion process

- Pitting corrosion
  - ✓ non-uniform, highly localized → pits

- Galvanic corrosion
  - ✓ two metals of different electrochemical potential in contact

Corrosion Control

- **Control rather than stop corrosion**

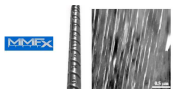
1. Barrier coatings
   - ❑ Standard paint isolates steel from moisture & must be repeated.

2. Sacrificial coatings
   - ❑ Metal pigments (zinc) become the anode, give up electrons to the steel, and corrode instead of the steel.

Corrosion Control

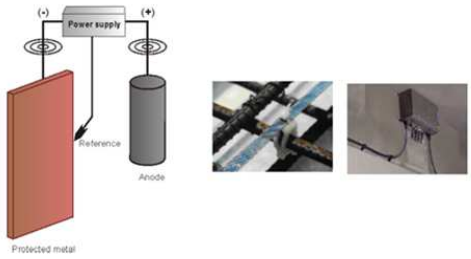
3. Special steel: weathering steel
   - Chemical process creates rust on surface which protects steel !

4. Corrosion resistant steels
   - Metal alloys are combined with steel
   - Example: MMFX steel.



Corrosion Control

5. Cathodic Protection



Aluminium

Aluminium

- Most plentiful metal on Earth
- High-energy requirements to extract it
  - recycling (25% of annual production)
- Alloying elements added for structural applications
- Production second to steel

Aluminium Compared to Steel

- Advantages
  - Lightweight (1/3 density of steel)
  - Good thermal & electrical conductivity
  - High strength-to-weight ratio
  - Corrosion resistant

  } attractive structural material

- Disadvantages
  - High initial cost
  - Lack of performance information

Aluminium Stress-Strain Curve