Week 2: Steel

Mostly an overview of Chapter 3, M&Z

CEE 363 Construction Materials

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Steel Topics

- Introduction to iron and steel
- Types of steel used in construction
- Steel production
- Iron-carbon phase diagram
- Heat treatment of steel
- Steel alloys
- Structural steel
- Reinforcing steel
- Mechanical testing of steel
- Steel corrosion
- Astec Industries
- Metals prices

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Introduction to Iron and Steel

- A few definitions and general descriptions are in order
  - Iron: Iron is an element and can be pure.
  - Cast iron: Iron that contains about as much carbon as it can hold which is about 4%.
  - Wrought iron: Iron that contains glassy inclusions.
  - Steel: Iron with a bit of carbon in it—generally less than 1%.

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Introduction to Iron and Steel

- A few definitions and general descriptions are in order
  - Pig iron: Raw iron, the immediate product of smelting iron ore with coke and limestone in a blast furnace. Pig iron has a very high carbon content, typically 4-5%, which makes it very brittle and not very useful directly as a material.

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A Selection of Mechanical Properties (from Gordon (1979))

Material	Tensile Strength (psi)	
Steel piano wire	450,000	
Commercial mild steel	60,000	
Cast iron	10,000 to 40,000 and higher	
Wrought iron	20,000 to 40,000	

Thermal Expansion of Various Materials (from CISPI (1994))

Material	in/in x 10^{-6}	in/100 ft. of pipe per 100°F
Cast iron	6.2	0.75
PCC	5.5	0.66
Steel (mild)	6.5	0.78
Steel (stainless)	7.8	0.94
PVC (high impact)	55.6	6.68
ABS (Type 1A)	56.2	6.75
Polyethylene (Type 1)	94.5	11.4

Introduction to Iron and Steel

- A few definitions and general descriptions are in order
  - Alloy steel: A generic term for steels which are alloyed with elements other than carbon. Why alloys? The mechanical behavior iron is changed hugely by the addition of carbon and other additives (or alloys).

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Types of steel used in construction

- Structural steel—plates, bars, pipes, structural shapes.
- Reinforcing steel—concrete reinforcement.
- Miscellaneous shapes for applications such as forms.

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Types of steel used in manufacturing construction equipment

- A36 plate at Astec Industries, Chattanooga, TN

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Types of steel used in manufacturing construction equipment

- A36 plate at Lafarge Cement Plant, Seattle. Part of a new kiln for making clinker (portland cement). Steel is 1.5 in. thick.

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Types of steel used in construction

"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." M&Z

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Types of steel used in construction

"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." M&Z

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Example of a local manufacturer

- Nucor Steel Seattle, Inc
- Location: West Seattle
- Nucor acquired assets for Birmingham Steel Dec 9, 2002.
- Annual capacity: 2.2 million tons
- Products
  - Carbon steel angles, channels, flats
  - Reinforcing bar

Typical shapes

- **Angle**
  Structural steel shape resembling L. May be Equal Leg Angle or Unequal Leg Angle. Used in trusses and built-up girders.
- **Channel**
  Structural steel shape which has a cross-section resembling [. Used in trusses and built-up girders.

Typical shapes

- **Plate**
  Sheet steel with a width of more than eight inches, with a thickness ranging from one quarter of an inch to more than one.
- **Flat-rolled steel**
  Category of steel that includes sheet, strip, and tin plate, among others. Produced by passing ingot/slab through pairs of rolls.
- **Reinforcing Bar (Rebar)**
  A commodity-grade steel used to strengthen concrete in highway and building construction.

Typical shapes

- **Sheet**
  Thin, flat-rolled steel. Coiled sheet steel accounts for nearly one-half of all steel shipped domestically and is created in a hot-strip mill by rolling a cast slab flat while maintaining the side dimensions. The malleable steel lengthens to several hundred feet as it is squeezed by the rolling mill. The most common differences among steel bars, strip, plate, and sheet are merely their physical dimensions of width and gauge (thickness).

Steel production

- Reduction of iron ore to pig iron.
- Refining pig iron to steel.
- Forming the steel into products.
- Refer to Fig 3.1, M&Z

Steel production (US stats)

Statistic	Million metric tons (2003)
Pig iron production	39.4
Steel production	91.5
Basic oxygen furnaces (%)	48%
Electric arc furnaces (%)	52%
Imports of steel products	21.7
Exports of steel products	8.2
Apparent steel consumption	104
Net import reliance	9%
Import sources: EU—18%, Canada—15%, Mexico—10%, Japan—7%, Other—50%	

World steel production

Statistics for raw steel	Million metric tons (2003)
US	91.5
Brazil	27.5
China	200
EU	159
Japan	110
Korea	46
Russia	61.2
Ukraine	38
World Total	924

Steel and aluminum recycling

Metal	Percentage Recycled
Iron and steel	55%
Aluminum	38%

For US only.

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Steel production

- Materials used to produce pig iron
  - Coal—as coke—used to supply carbon. In a blast furnace, ore is heated in the presence of carbon—this allows oxygen in the ore to react with carbon to form gases.
  - Limestone—helps to remove impurities
  - Iron ore—processed ore at the start of the process has about 65% iron.
  - Impurities (slag) float on the top of melt.
- Requires about 3.2 tons of raw materials to produce 1.0 ton of steel.

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Steel production

- Three types of furnaces have been used for refining pig iron (or scrap steel) to refined steel
  - Open hearth (no longer used the US)
  - Basic oxygen
  - Electric arc

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Iron-carbon phase diagram

- To refine steel from either scrap or pig iron, the amount of carbon must be carefully controlled.
- In M&Z, Fig 3.2 shows a typical iron-carbon diagram. This helps us to understand how this control is done.
- A slightly more colorful version of the iron-carbon phase diagram follows.

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Iron-carbon phase diagram--terms

- Ferrite (α): Iron in a BCC structure. Maximum solubility of carbon in ferrite is low (0.02%C).
- Austenite: Iron with a FCC structure. Due to FCC structure, more carbon atoms can be accommodated. Maximum solubility of carbon in austenite is 2.11%.
- Cementite (or iron carbide): This forms when solubility of carbon in solid iron is exceeded. Fe_3C contains 6.67%C. Cementite is present in all commercial steels.
- Pearlite: Lamellar structures of α ferrite and cementite.

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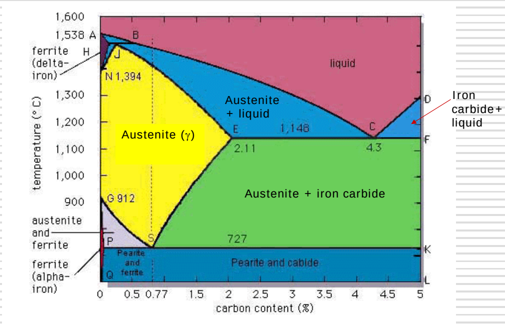
Iron-carbon phase diagram



Iron-carbon phase diagram

- Ferrite, pearlite, and iron carbide greatly influence the properties of steel.
  - Ferrite has relatively low strength but is very ductile.
  - Iron carbide has high strength but little ductility.
  - Combining these two in different proportions alters the mechanical properties of steel.
  - In general, increasing carbon content increases the strength but reduces ductility.

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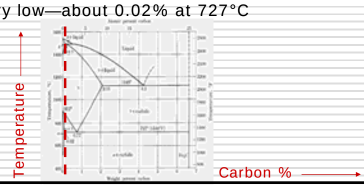
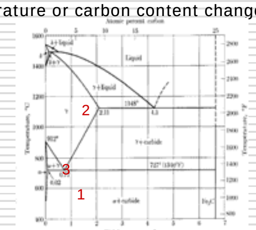
Iron-carbon phase diagram

- Left side—pure iron (0% carbon) goes through two transformations as temp increases
  - Pure iron below 912°C has BCC crystalline structure called ferrite.
  - At 912°C, ferrite changes to a FCC structure called austenite (γ).
  - At 1394°C, iron returns to a BCC structure.
  - The high and low ferrites identified as δ and α ferrite.
- Carbon goes into solution with α ferrite at temps between 400°C and 912°C—but solubility limit for carbon is very low—about 0.02% at 727°C



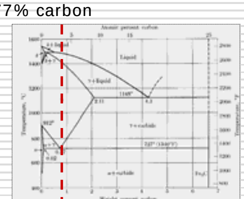
Iron-carbon phase diagram

1. At low temps and to the right of the solubility limit line, α ferrite and iron carbide (Fe_3C) coexist.
2. From 727°C to 1148°C, the solubility of carbon in the austenite increases from 0.77 to 2.11%. The solubility of carbon in austenite is greater than in α ferrite because of the FCC structure of austenite.
3. At 0.77% carbon and 727°C, a eutectoid reaction occurs, that is, a solid phase change occurs when either the temperature or carbon content changes.



Iron-carbon phase diagram

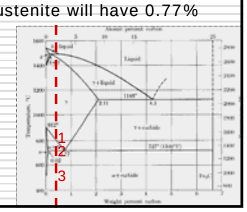
- The eutectoid reaction describes the phase transformation of one solid into two different solids (or $S_1=S_2+S_3$). In the Fe-C system, there is a eutectoid point at approximately 0.77% carbon, 727°C. The phase just above the eutectoid temperature for plain carbon steels is austenite—as noted previously. Consider what happens as this phase is cooled through the eutectoid temperature (727°C).
- Austenite –> ferrite + iron carbide (Fe_3C). Thus, the steel has 0.77% carbon



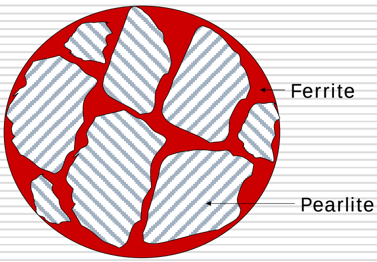
Iron-carbon phase diagram

- At carbon contents less than eutectoid composition, hypoeutectoid (or containing less than 0.77% carbon) alloys are formed. Most structural steels are hypoeutectoid (about 0.1 to 0.3% carbon).

1. For example, at 0.25% carbon, and above about 810°C, solid austenite exists as grains of uniform material. As the temp drops, α ferrite is formed from 810 to 727°C and accumulates at the grain boundaries of the austenite.
2. At temps slightly above 727°C, the ferrite will have 0.02% carbon in solution and austenite will have 0.77% carbon.
3. When temp drops below 727°C, the austenite will transform to pearlite (alternate layers of α ferrite and iron carbide). Pearlite is not a phase but a mixture of two phases. Refer to next image.



Pearlite and Ferrite below 727°C



Iron-carbon phase diagram

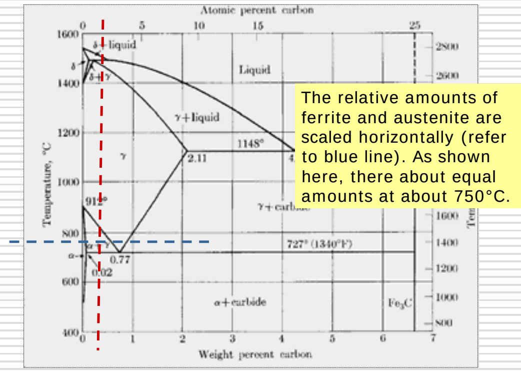
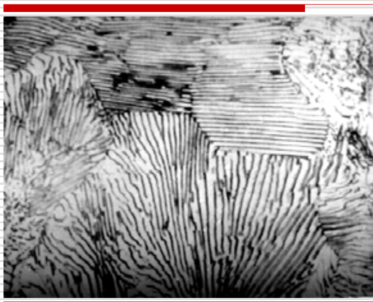


Image of pearlite



Light colored material is ferrite and dark material is iron carbide.

Heat treatment of steel

- Properties of steel can be altered by applying a variety of heat treatments.
  - Annealing: Heat to austenite range (about 10°C above the austenite line) then slowly cool to room temp. Results in softer steel, reduced internal stress, increases ductility and toughness.
  - Normalizing: Same as annealing but heat to 40°C above the austenite line. Then air cool. Produces a uniform, fine-grained structure. Considered as a corrective treatment and not for strengthening.

Steel alloys

- Alloy agents are added to improve one or more of the following properties
  - Hardness
  - Corrosion resistance
  - Machineability
  - Ductility
  - Strength
- Typical alloys are shown in Table 3.1, M&Z.

Steel alloys

- Structural steels based on composition
  - Carbon or carbon-manganese steels
  - High strength low alloy steels (HSLA)
  - High strength quenched and tempered alloy steels
  - Read the content in the pdf file from MIT, Civil and Environmental Engineering Dept, Spring Semester 1999 entitled “Chemical Composition of Structural Steels.”

Structural steel

- Structural steel grades in the US (but not limited to)
  - ASTM A36—be careful, this one is being replaced by ASTM A992. Thus, info in M&Z needs a little updating.
  - ASTM A529
  - ASTM A572
  - ASTM A242
  - ASTM A588
  - ASTM A514
  - Refer to additional details in Table 3.2, M&Z.
  - Be careful—should always obtain information on locally available grades and changing grades.
    - ASTM A992
    - ASTM A852

Structural steel specifications

- City of San Diego—refer to pdf on class web site.
- WSDOT Standard Specifications—Division 6 Structures. Go to Section 6-03 Steel Structures, page 6-108. URL is
  - http://www.wsdot.wa.gov/fasc/EngineeringPublications/Manuals/SS2004.PDF

Structural steel specifications

- Bridges
  - American Association of State Highway and Transportation Officials (AASHTO)
  - For example, WSDOT Standard Specifications refer to AASHTO M 270. What is this?
    - "Carbon and High-Strength Low-Alloy Structural Steel Shapes, Plates, and Bars and Quenched and Tempered Alloy Structural Steel Plates for Bridges"

Structural steel specifications

- Bridges
  - AASHTO M 270 continued
    - "This specification covers carbon and high-strength low-alloy steel structural shapes, plates, and bars and quenched and tempered alloy steel for structural plates intended for use in bridges. Six grades are available in four yield strength levels."

Structural steel

- Structural steel shapes
  - W: Wide-flange
  - HP: Wide-flange
  - M: Wide-flange
  - S: I-beam
  - C: Channel
  - MC: Channel
  - L: Angle
  - Refer to Fig 3.5, M&Z.
  - Refer to ASTM A6 "Standard Specification for General Requirements for Rolled Steel Plates, Shapes, Sheet Piling, and Bars for Structural Use."

Structural steel question

- Is it always better to specify shapes with the highest possible strength?

Reinforcing steel

- PCC has little tensile strength, thus structural PCC members subjected to tensile and flexural stresses must be reinforced.
- Can be produced in four grades: 40, 50, 60, and 75 ksi.
- Refer to Table 3.3, M&Z.

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Reinforcing steel specifications

- WSDOT Standard Specifications, Section 9-07.2 "Deformed Steel Bars"

  "Deformed steel bars for concrete reinforcement shall conform to the requirements of AASHTO M 31, Grade 60 or ASTM A706.
  - AASHTO M 31 "Deformed and Plain Billet-Steel Bars for Concrete Reinforcement." This specification is the same as ASTM A615.
  - ASTM A706: "Low-Alloy Steel Deformed and Plain Bars for Concrete Reinforcement"
  - Billet-steel simply refers to a type of section (or block) of steel prior to rolling into a final shape or product.

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Reinforcing steel sizes

Bar diameter (in.)	US Customary (1/8's of an inch)	Metric (diameter, mm)
0.375	#3	#10
0.500	#4	#13
0.625	#5	#16
0.750	#6	#19
0.875	#7	#22
1.000	#8	#25
1.128	#9	#29
1.270	#10	#32
1.410	#11	#36
1.690	#14	#43
2.260	#18	#57

Mechanical testing of steel

The major tests are:

- Tension test—you will do this one in lab as a group.
- Torsion test
- Charpy V Notch Impact Test—a measure of toughness. This will be demonstrated in lab.
- Bend test
- Hardness test—this will be demonstrated in lab.

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Tension test

- Refer to ASTM E8 "Standard Test Method for Tension Testing of Metallic Materials" (also AASHTO T 68)
- Determine (refer to Figs 3.9—3.10, M&Z)
  - Yield strength
  - Yield point elongation
  - Tensile strength
  - Elongation
  - Reduction of area
- Testing done at room temperature

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Tension test in CEE Lab

- Report material property items shown in ASTM E8
  - Yield strength and method used to determine yield strength
  - Yield point elongation
  - Tensile strength
  - Elongation
  - Reduction of area
  - ….and modulus of elasticity.

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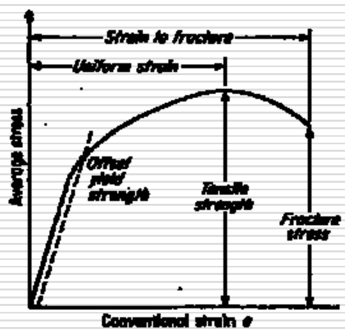
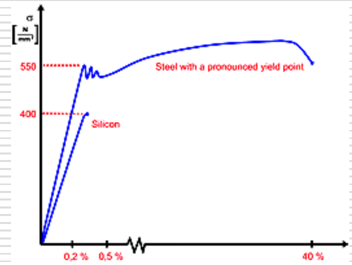
Tension test in CEE Lab



Tension test in CEE Lab



Impact test

- Refer to ASTM E23 "Standard Test Methods for Notched Bar Impact Testing of Metallic Materials"
- Also designated AASHTO T 266.
- Used to measure the "toughness" of the material—or more to the point—the energy required to fracture a V-notched simply supported specimen.
- Energy measured in m-N (ft-lb). This value is compared to allowable specification values.

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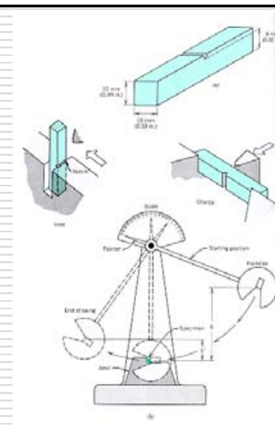
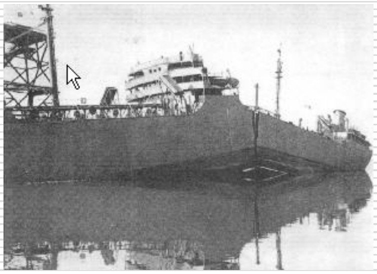
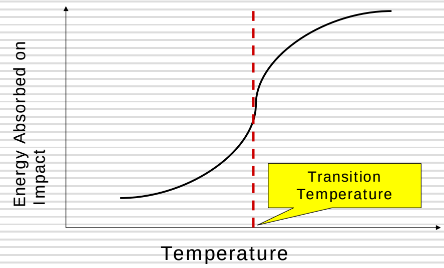


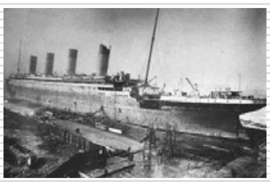
Example—Tanker constructed for WW2



Impact Test Transition Temperature

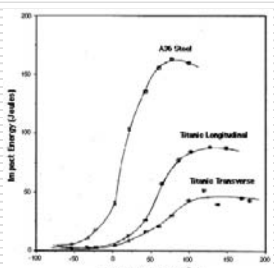


Example—steel from Titanic



Conversion: joulesx0.74=ft-lb

Titanic steel plate had a Charpy Value of about 4 ft-lb at 0°C (which was appropriately the water temperature the night of the sinking)



Mechanical properties of Titanic steel from hull

Property	Result
Yield Strength	28 ksi (193.1 MPa)
Tensile Strength	60 ksi (417.1 MPa)
Elongation	29%
Reduction in Area	57.1%

Chemical composition of Titanic steel from hull (%)

One of the issues with the steel hull plate from the Titanic is the relatively high amounts of phosphorus and sulfur.

Source of Steel	C	Mn	P	S	Si	Cu	O	N	MnS Ratio
Hull Plate from Titanic	0.21	0.47	0.045	0.069	0.017	0.024	0.013	0.0035	6.8:1
Sample from Gate—Ship Canal Locks	0.25	0.52	0.010	0.03	0.02	--	0.018	0.0035	17.3:1
A-36	0.20	0.55	0.012	0.037	0.007	0.01	0.079	0.0035	14.9:1

Ship Canal steel from Chittenden Ship Canal Lock, Seattle

Impact test example specification

- WSDOT Standard Specifications, Section 6-03.2 Materials.
  - "All AASHTO M 270 material used in what the Plans show as main load carrying tension members or as tension components of flexural members shall meet the Charpy V-notch requirements of AASHTO M 270 temperature zone 2. All AASHTO M 270 material used in what the Plans show as fracture critical members shall meet the Charpy V-notch requirements of AASHTO M 270, Fracture Critical Impact Test Requirements, temperature zone 2."
  - So what are the Charpy requirements in AASHTO M 270?

Impact test example specification

- So what are the Charpy requirements in AASHTO M 270?
  - Two tables in AASHTO M 270—non-fracture critical impact test requirements and fracture critical impact test requirements. These are minimum test requirements.
  - Function of steel grade, thickness and joining method and temperature zone (there are three of these).
  - Example for non-fracture critical
    - 36T, Zone 1: 15 ft-lb at 70°F
    - 36T, Zone 2: 15 ft-lb at 40°F
    - 36T, Zone 3: 15 ft-lb at 10°F
  - Example for fracture critical
    - 36F, Zone 1: 25 ft-lb at 70°F
    - 36F, Zone 2: 25 ft-lb at 40°F
    - 36F, Zone 3: 25 ft-lb at 10°F

Note: 36T and 36F refers to a specific grade of steel.

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Hardness test

- Often used in specifying machine parts and tools or the effect of heat treatments.
- A frequently used hardness test for steel is the Rockwell Hardness Test.
- ASTM E18 (or AASHTO T 80) "Standard Test Methods for Rockwell Hardness and Rockwell Superficial Hardness of Metallic Materials"
- ASTM A370 "Standard Test Methods and definition for Mechanical Testing of Steel Products" contain correlations between Rockwell hardness numbers and approximate tensile strength of the steel.

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Steel corrosion

- Corrosion is estimated to cause $276 billion in damage in the US each year. Much of this corrosion is due to iron and steel.
- Some State DOTs, such as the Florida DOT do an extensive amount of corrosion related testing for bridges.

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Steel corrosion

- Carbon steel accounts for approximately 85%, of the annual steel production worldwide—and—importantly—carbon steel has relatively limited corrosion resistance. This type of steel is used in large tonnages in:
  - Marine applications
  - Nuclear power
  - Fossil fuel power plants
  - Transportation
  - Chemical processing
  - Petroleum production and refining, pipelines
  - Mining and construction
  - Metal-processing equipment.

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Steel corrosion

- Defined in M&Z as the destruction of a material by electrochemical reaction to the environment.
- Corrosion requires four processes
  - Anode—the corroding metal (steel).
  - Cathode—the reduced metal.
  - Conductor—the steel in this case.
  - Electrolyte—a liquid (or gas) that supports the flow of electrons.
- Corrosion process is analogous to a car battery.

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Steel corrosion

- Methods for corrosion resistance
  - Barrier coatings: Isolate steel from moisture and oxygen. Metallic coatings fit into this category including galvanized coatings such as hot dipped zinc (hot dipped zinc coating is applied to steel at a temperature of about 450°C).
  - Inhibitive primer coatings
  - Sacrificial primers (cathodic protection): Typically this type of coating is zinc. The zinc becomes an anode and, in effect, "corrodes" in lieu of the steel it is protecting. Thus zinc coatings can protect steel as a sacrificial anode and as a barrier coating.

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Steel corrosion

- Other preventive measures (some not directly addressed by M&Z):
  - Modify the environment
  - Modify the properties of a metal
  - Install a protective coating over the metals
  - Impose an electric current to supply electrons
  - Change to non-metallic materials

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Steel corrosion

- Chrysler Building built in NYC in 1930 is clad with stainless steel (302 stainless). This helped achieve the art-deco style.
- Stainless steel is a family of steels that contain a minimum of 10.5% chromium.
- Chromium in contact with oxygen forms a chromium oxide film a few microns thick. That is how stainless steel has substantially reduced corrosion.
- So, can stainless steel corrode? Yes! However at a substantially reduced rate when compared to unprotected carbon steel.

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Supplemental photos—manufacturing of paving equipment

- Photos taken June 2004 at Astec Industries, Chattanooga, TN.
- Astec and Roadtec manufacture heavy equipment for highway construction such as
  - Hot mix plants
  - Milling machines
  - Paving machines

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Astec manufacturing site, Chattanooga, TN

Don Brock, CEO, Astec Industries

Roadtec Industries, paving machines

Astec plant located in Alabama

HMA storage silo

Roadtec paving machine and Shuttle Buggy

Steel plate for new paving machine, Roadtec Industries

Plate stock for hot mix plant, Astec Industries

Bending plate, Astec Industries

A different view of bending plate

End result

Hot mix plant being manufactured, Astec Industries

Metals prices

- Steel (hot rolled plate)
  - January 2003: $0.15/lb
  - January 2005:$0.34/lb
- Aluminum alloy
  - April 2005: $0.85/lb
- Titanium
  - April 2005: $4/lb

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References

- Mamlouk, M. and Zaniewski, J. (1999), “Materials for Civil and Construction Engineers,” Addison Wesley Longman, Inc.
- Gordon, J.E. (1976), “The Science of Strong Materials,” Princeton Paperbacks.
- CISPI (1994), “Cast Iron Soil Pipe and Fittings Handbook,” URL: http://www.cispi.org/handbook.htm

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