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Practical Steel Metallurgy for the Structural Steel User

What you need to know about Steel Metallurgy

Doug Rees-Evans
Steel Dynamics, Inc.
Structural and Rail Division
Columbia City, IN 46725
Welcome

Audience:
- Engineers / Architects
- Fabricators
- Steel Users / Purchasers
- Students
- General Interest
- Metallurgists

Approach:
- “Hit the High-Points”
  - Additional information given in slides for self-study.
- Practical Focus
Questions

• Iron – Steel: What is the Difference?
• Why are there multiple Grades of Steel? Isn’t steel, steel?
• How can a mill control chemistry? Isn’t it dependent upon what scrap is used?
  o How does a mill control the properties of a steel product?
• If I retest a product, will I get the same results as in the MTR?

Iron – Steel: What is the Difference?

Steel

Steels can be classified in a number of ways:

• major alloying element(s),
• microstructural makeup,
• processing method(s),
• intended application(s).
Iron – Steel: What is the Difference?

**Steel**

Our discussion will be limited to Carbon-Steels

Aka:

- Carbon steel
  - Mild Steel (\(\%C \leq .25\%\))
  - Medium Carbon Steel (\(.25\% > \%C \geq .45\%\))
  - High Carbon Steel (\(.45\% > \%C \geq 1.5\%\))
- Carbon – Manganese steel (C-Mn)
- High Strength – Low Alloy Steel (HSLA)
  - HSLA = C-Mn Steel + micro-alloy (eg. V, Nb) in low concentrations

Iron – Steel: What is the Difference?

**Iron**

- a magnetic, silvery-grey metal
- 26th Element in the Periodic Table
- Symbol: Fe (Latin: Ferrum)
- 4th most abundant naturally occurring terrestrial surface element
Iron – Steel: What is the Difference?

Iron

- Very reactive (O, S, Cl), thus not found naturally occurring in the metallic state.
- Found in nature as (ores):
  - Oxides
  - Sulfides
  - Carbonates
  - Chlorides
- Ores also include impurity elements: S, P, Mn, Si, ...
- ‘pure’ metallic Iron of little commercial use.

Iron – Steel: What is the Difference?

Iron-based Building Materials

- Mixtures (Alloys) of other elements in Iron
- Iron-based Alloys commonly classified by the major alloying constituent(s).

> Carbon
- Carbon Steel
- Cast Iron
- Wrought Iron
- Pig Iron (Hot Metal)

> Other than carbon (Ni, Cr, Mo, W, ...)
- Stainless Steel
- Alloy Steel
Iron – Steel: What is the Difference?

Short Answer:
<< based upon the chemical makeup of the material >>

- **Iron**: An element metal.

- **(Carbon) Steel**: a series of alloys that has more Iron (by mass) than any other element, and a maximum Carbon content of less than **2 wt%**.
  - Secondary alloying element is typically Manganese (Mn)

- **Cast Iron**: a series of alloys that has more Iron (by mass) than any other element, and a minimum carbon content of **2 wt%** (typical max: 4 wt% C).
  - Secondary alloying element is typically Silicon (Si)

---

Iron – Steel: What is the Difference?

Short Answer:
<< based upon the chemical makeup of the material >>

- **Wrought Iron**: the metallic product of the Puddle Furnace
  - Can be considered the precursor of modern low - mild carbon steels
  - OBSOLETE

- **Pig Iron**: the solid metallic product of the Blast Furnace (typically 3.5 – 4.5 wt% C, with 1 – 2.5 wt% (ea.) of Mn, and Si).
  - In the liquid state is commonly known as "Hot Metal"
  - No "structural" uses. Manufactured as the feed-stock for Steelmaking and Cast Ironmaking.
Iron – Steel: What is the Difference?

Chemistries

Q. Why separation @ 2 wt%?

A. Phase Diagram.

CAST IRONs

CAST IRON:

2 - 4% : Cast Iron

CARBON STEELS

1 - 2% : Ultra High Carbon Steel

.05 - .25% : Wrought Iron

<.05% : Ultra-Low Carbon Steel

.05 - .15% : Low Carbon Steel

<.05% : Ultra-Low Carbon Steel

.15 - .30% : Mild Steel

.30 - .60% : Medium Carbon Steel

.60 – 1% : High Carbon Steel

1 – 2% : High Carbon Steel

2 - 4% : Cast Iron

Common Structural Applications: Shapes, Bars, Bolts, Plates, etc.

Metallurgy Basics

Phase Diagram

A graphical representation of composition and temperature limits for the existence of different phases within an alloy system (at equilibrium).

- Temperature vs. Composition
- Solid Lines delineate Phases
- Crossing a phase line (@ constant composition) results in a phase change. (L ↔ S, L ↔ L + S (mushy), S ↔ S', S ↔ S' + S'', etc.)

Example:

Hypothetical Chocolate- Vanilla Phase Diagram

Cooling of a composition (green arrow)
- Temp 1: Homogeneous Liquid (H)
- Temp 2: Solidification of Solid (CC) from the liquid
- Temp 2 – 3 : Mushy (Liquid VM + Solid CC)
- Temp 3: Solidification of Liquid VM : Duplex Structure = Ripple

Upon Heating, reactions are reversible.
Iron – Steel: What is the Difference?

**Q. Why separation between Cast Iron and Steels @ 2 wt% C?**

**Iron – Steel: What is the Difference?**

**Long Answer:**

The properties of Iron – Carbon alloys are controlled by the **microstructure** of the material, which consequentially are determined by the chemistry and processing of the material.
Iron – Steel: What is the Difference?
Iron - Carbon Alloys

One of the most important properties of Iron is its’ **allotropic** nature.

**Allotropic** = Has different crystal structures at different temperatures.

Basic Metallurgy
Nature of Metals

- **crystalline**: in the solid state, a metal’s atoms are arranged in an orderly repeating 3-D pattern (crystal lattice).
  
- smallest symmetric arrangement of atoms = **unit cell**

![Unit cell and crystal lattice diagram](image)
Basic Metallurgy

Crystal Space Lattices

- 14 different types of crystal “space lattices”.
- 3 most common (favored by metals)

**BCC**
Body-Centered Cubic
{Cr, Mo, Nb, V}

**FCC**
Face-Centered Cubic
{Al, Cu, Ni}

**HCP**
Hexagonal Close-Packed
{Co, Ti}

Basic Metallurgy

Nature of Metals

- intersection of crystal lattices of differing spatial orientations create grain boundaries

2-D schematic

metallographic appearance of grain boundaries

Each grain will have a different “crystallographic” orientation than its neighbor
Iron – Steel: What is the Difference?

Iron Allotropism

Iron Allotropism

The existence of two or more different physical forms

Phase Diagram of “Pure” Iron

2 “BCC” Allotropes (Phases)
- δ-Iron (2541 - 2800°F)
- α-Iron (≤ 1670°F)

1 “FCC” Allotrope (Phase)
- γ-Iron (1670 - 2541°F)

Carbon in an Iron Crystal Lattice

Atomic radii (Angstroms)
- Carbon : 0.7
- Iron : 1.4

Defect in Crystal Structure:
- A: Interstitial Solute
- B: Substitution Solute
- C: Dislocation (planar)
- D: Vacancy

Basic Metallurgy

Carbon in an Iron Crystal Lattice
**Basic Metallurgy**

**Iron Allotropism**

- **γ-Iron (FCC)** “Austenite” > 1670°F
- **α-Iron (BCC)** “Ferrite” ≤ 1670°F

### Unit Cells (Angstroms)
- 3.57 γ-Iron
- 2.57 α-Iron

### Max Carbon Solubility (wt%)
- 2.01% γ-Iron
- 0.02% α-Iron

**Problem upon Cooling:**

Carbon Solubility Difference (2 orders of magnitude)

---

**Basic Metallurgy**

**Austenite to Ferrite Phase Transformation**

- Max Carbon Solubility: 2.01% (wt%)
- Max Carbon Solubility: 0.02% (wt%)

- "New Phase" • C-rich
- Morphology: Volume % and spacing Dependent upon:
  - Wt% C
  - Other alloying elements
  - Cooling rate.
- **Upon Heating:**
  - α → γ
  - Fully reversible
- **Upon cooling**
Basic Metallurgy
Austenite to Ferrite Phase Transformation
At equilibrium in Steel

**Fe₃C | Cementite:**
- 6.67 wt% C
- Strong
- Hard
- Wear-Resistant
- Brittle
- Un-Weldable

**α-Iron | Ferrite:**
- 0.02 wt% C
- Weaker
- Soft
- Ductile
- Weldable

**Pearlite:** a two-phased, lamellar structure composed of alternating layers of ferrite and cementite.

*technically: is a colony – not a “grain”.*

**Equilibrium Microstructures**
Varying Carbon content yields varying microstructures

- ~ 0.02 wt% C
- ~ 0.20 wt% C
- ~ 0.40 wt% C
- ~ 0.80 wt% C
- ~ 1.00 wt% C
**Basic Metallurgy**

**Austenite to Ferrite Phase Transformation**

Non-Equilibrium Steel Phases:
- Upper & Lower Bainite
  - Highly variable microstructures (dependent upon alloy content and cooling rates)
  - Low C: low temp toughness, improved strength, weldability.
- Martensite
  - Low: ductility, & fracture toughness
  - Very: strong, hard, & wear resistant

**Carbon Solubility:**
\[ \gamma (2.01\%) \rightarrow \alpha (0.02\%) \]

**Diffusion:**
Temperature • Time Reaction

If insufficient Time or Temperature is provided (ie. Rapid cooling), carbon will be "trapped" in a non-equilibrium position.

---

**Basic Metallurgy**

**Austenite to Ferrite Phase Transformation**

**Non-equilibrium in Steel**

**TTT Diagram for Eutectic Steel**

- Curve shapes shift and change shape in response to alloying additions

(Courtesy of Metallos)

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Author: Metallos
Basic Metallurgy

Austenite to Ferrite Phase Transformation
At equilibrium in Cast Iron

Gray Iron
• 3D network of graphite flakes in Pearlitic matrix

Ductile / Nodular Iron
• addition of elements (Mg) result in formation of graphite nodules instead of flakes.

- Graphite = soft, low strength, acts like a “void”.
- Flakes morphology = stress risers
- Low Strength
- Low Ductility
- LOW NOTCH TOUGHNESS
  ✓ Excellent machinability
  ✓ Good compressive strength
  ✓ Excellent “castability”

Cast Iron

Historic Structural Uses

Static / Compressive
Cast Iron
Historic Structural Uses

“Iron Bridge”
across the River Severn
Coalbrookdale, Shropshire, UK

1st CAST IRON BRIDGEWORK

Opened: 1781
Closed to traffic: 1934, still standing
UNESCO “World Heritage Site”

Length: 60m,
Longest Span: 30.5m,
Clearance: 18m

800+ casting : 379 tons of iron
built on carpentry joinery principles
(mortise and tenon, blind dovetails)

Cost (in 1781): £6,000

Cast Iron
Historic Structural Uses

After example of the 1781 “Iron Bridge”:
1830’s – 1840’s: 1,000’s of Cast Iron based bridges put into RR service.

Cast Iron Bridge Experiences: 1830 - 1891

Dee Bridge, Chester, Cheshire, UK
Failure: 24 May 1847. 5 fatalities. Fracture of CI beam

Wootton Bridge, Wootton, UK
Failure: 11 June 1860. 2 fatalities. Fracture of CI beam

Bull Bridge, Ambergate, UK
Failure: 26 Sep 1860. 0 fatalities. Fracture of CI beam

Ashtabula River Bridge, Ashtabula, OH
Failure: 29 Dec 1876. 52 fatalities, 64 injuries. Fatigue (7) of CI beam.

Tay Rail Bridge, Dundee, Scotland
Failure: 28 Dec 1879. 75 fatalities. Wind load - Failure of CI to wrought Iron connections.

Norwood Jct Rail Bridge, Norwood, UK
Fracture & Repair of CI beams due to derailment (impact?): Dec 1876
Failure: 1 May 1891. 0 fatalities. Failure of CI beams.

CAST IRONS not suitable for Tension nor Cyclic Loading

Graphite = soft, low strength, acts like a “void”.
Flakes morphology = stress risers
Low Strength, Low Ductility
LOW NOTCH TOUGHNESS
Iron – Steel: What is the Difference?

**CAST Steel ≠ CAST Iron**

**Cast Steels**
- Any “steel” composition
- Variable Cast Grain Structures
  - Chill Zone (equiaxed)
  - Columnar
  - Equiaxed Zone
  - ✔ Ferrite
  - ✔ Pearlite

**Cast Iron**
- Pearlite + Graphite

---

Iron – Steel: What is the Difference?

**Low C / Mild Steel vs. WROUGHT Iron**

- Steel – Bessemer, Open Hearth, BOF, EAF (from the liquid)
- Wrought Iron = Puddling (not fully liquid = “pasty”) ⇒ Rolling ⇒ Slitting ⇒ Reheating ⇒ Forging/Re-Rolling (Merchant Bar)
  - Chemistry (typical – wt%): C ≤ .25, Mn ≤ .05, S ≤ .03, P .10 – .12, Si .10 – .15
    - Period literature reports: .05 – .15 wt% C as usual analysis
  - Mechanical Properties (typical – wt%):
    - Strength: Yield – 23ksi Tensile – 46ksi
    - Elongation (in 8”): 26%
    - High fraction (typ. 2-3% volume fraction) of oriented slag inclusions
      - Period literature claims slag content benefits ductility and malleability – more likely due to very low C / Mn.
      - OBSOLETEx (quality and manufacturing cost)
Iron – Steel: What is the Difference?

**WROUGHT Iron**

The Eiffel Tower
Paris, France
Built 1889
Designer: Gustave Eiffel
Material: Puddle (Wrought) Iron

“Heated and Hammered Bars”

From: Sir Henry Bessemer, F.R.S
AN AUTOBIOGRAPHY WITH A CONCLUDING CHAPTER.
Universal Press, London 1895.

“Mild” Bessemer Steel
Puddle (Wrought) Iron

Wrought Iron = prone to “delaminate”

---

Iron – Steel: What is the Difference?

“Long Answer”: The difference is.....

• Iron is an Element;
  ✓ Steel is a series of alloys based on the element Iron

• If referring to “Cast Irons” as “Iron”:
  ✓ Cast Irons differ greatly from steel in chemistry (carbon content), and microstructure.
  ✓ Cast STEEL ≠ Cast IRON.

• If referring to “Wrought Iron” as “Iron”:
  • Although similar in carbon content to low carbon / mild steels, Wrought Iron differs greatly in bulk chemistry, method of manufacture, and microstructure (large slag volume content); and consequently applicability.
Questions

✓ Iron – Steel: What is the Difference?
➢ Why are there multiple Grades of Steel? Isn’t steel, steel?
• How can a mill control chemistry? Isn’t it dependent upon what scrap is used?
  o How does a mill control the properties of a steel product?
• If I retest a product, will I get the same results as in the MTR?

Why Multiple Grades?

What is a Grade?

Webster’s

Grade ‹ˈɡrād› n (1659) 1: to arrange in a scale or series
     (1796) 2a: a position in a scale of rank or qualities.
     b: a standard of quality

Examples of Structural Steel Grades

A572 - Grades 42,50,60,65
A36, A992

} definition 1, 2a
}) Standard loosely definition 2b
What is a Grade?

Classification / systematic arrangement / division of steels into groups based upon some common characteristic(s).

Characteristics:
- Composition / Chemistry
  - Principle alloying element:
    - C-Steels, Ni-Steels, Cr-Steels, Cr-V-Steels, etc.
  - Quantity of principle alloying element:
    - Low-C, Mild, Med-C, High-C, etc.
- Manufacturing / processing method(s)
  - Rimmed / Capped / semi-killed / killed
  - Hot Rolled / Cold rolled
  - Heat treated
- Product Form
  - Bar, plate, sheet, strip, tubing, structural shape, etc.

What is a Grade?

Metal classifications, other than Carbon and Alloys Steels, are generally made by:
- Grade: denotes chemical composition
- Type: denotes deoxidation method
- Class: denotes some other attribute
  - Strength, etc...

Our industry, however, tends to use grade, type and class interchangeably.

Eg: ASTM A572 grade 50 (A572-50): “50” is a strength level (min 50ksi fy).


*Grade: Specification detailing chemical and mechanical property requirements/restrictions*
Why Multiple Grades?
Specification Issuing Bodies

- AASHTO: Association of American State Highway Transportation Officials
  - Focus: Bridge & Highway
- ABS: American Bureau of Shipping
  - Focus: Ship Building
- API: American Petroleum Institute
  - Focus: Petroleum Industry
- ASTM: ASTM International
  - Focus: General/Specific
- CSA: Canadian Standards Association
  - Focus: For use in Canada
- SAE: Society of Automotive Engineers
  - Focus: Automotive
+ many others.

Why Multiple Grades?
The different Specification Issuing Organizations may adopt & adapt different “grades”

Example: AASHTO M270M/M270 vs ASTM A709/A709M vs ASTM A572/A572M
- ASTM controls and issues Specification A572
- ASTM A572 has various strength levels: eg. 50 [345] (ksi [MPa]).
- ASTM A572 = riveted, welded, bolted structures (general applications).
- AASHTO has incorporated ASTM A572 gr 50 into their M270M/M270 specification for use in bridge construction (M270M gr 345).
- By agreement, the AASHTO M270M/M270 specification is republished by ASTM as specification A709/A709M.

Thus:

**ASTM A709-50 ≈** AASHTO **M270M-345 ≈** ASTM **A572-50**

* some differences may exist due to committee activity and publishing cycles and actual intended applications.
Why Multiple Grades?
Specific Product Application

Example: ASTM A709-50 vs ASTM A709-50Tx vs ASTM A709-50Fx
* "x" = 1, 2, or 3 – represents specific "zone" / minimum service temperature

- A709-50 = “base grade” – “general” bridge
- Due to SPECIFIC product application, SPECIFIC additional requirements (CVN Testing) is required.
- Non-Fracture Critical: (Grade designation: A709-50Tx)
  - main load carrying member
  - Has redundancy or failure not expected to cause collapse
- Fracture Critical: (Grade designation: A709-50Fx)
  - main load carrying tension member or tension component of bending member
  - Failure expected to lead to collapse

A709 CVN Testing Requirements (≤ 2” Shape)

<table>
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<tr>
<th>Fracture &quot;Condition&quot;</th>
<th>Zone 1</th>
<th>Zone 2</th>
<th>Zone 3</th>
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<tr>
<td>Non-Critical (T)</td>
<td>15 @ 70°F; 15 @ 40°F; 15 @ 10°F</td>
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<tr>
<td>Critical (F)</td>
<td>25 @ 70°F; 25 @ 40°F; 25 @ 10°F</td>
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<tr>
<td>Service Temperature</td>
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<td></td>
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<tr>
<td>(°F)</td>
<td>0°F</td>
<td>&gt;0°F to -30°F</td>
<td>&gt;-30°F to -60°F</td>
</tr>
</tbody>
</table>

A709-50T1 = A709-50 + T1 CVN requirements (min 15 ft-lbf @ 70°F)
- Redundant main load carrying member (non-fracture critical) for use at or above 0°F

A709-50F3 = A709-50 + F3 CVN requirements (min 25 ft-lbf @ 10°F)
- Non-Redundant main load carrying tension member (Fracture Critical) for use between -30 to -60°F
**Why Multiple Grades?**

Additions / Restrictions

Example: ASTM A572-50 vs ASTM A992 (Structural Shapes)

- ASTM A572-50 vs ASTM A992 = both 50ksi [345 MPa] min fy
- ASTM A572-50
  - Originally published by ASTM 1966
  - Predominately OH and BOF mills, limited EAF mills (domestic production)
  - HSLA (Nb-V) C-Mn Steel
  - Low residuals (Cu, Ni, Cr, Mo) - $$$ to add
- ASTM A992
  - Originally published by ASTM 1998 (W Shapes)
  - (1998 domestic production): No OH nor BOF. 100% EAF
  - residuals (Cu, Ni, Cr, Mo) in feed stock (scrap)
  - A572-50 “based” w/ restrictions:
    - residuals, max fy, max yield/tensile ratio, max CE.

---

**Why Multiple Grades?**

Different Products

**Pancakes:**
2 Cups Baking Mix 2 Tbsp. sugar
1 1/3 cups milk 1 egg
• Stir ingredients together until blended.
• Bake on hot, lightly greased griddle …

**Waffles:**
2 Cups Baking Mix 2 Tbsp. sugar
1 1/3 cups milk 1 egg
• Stir ingredients together until blended.
• Pour onto hot waffle iron…

- Same chemistry
- Deviation in Processing – Different Product
- Might or Might Not be in same specification.
### Why Multiple Grades?

**Multi-Certification**

<table>
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<tr>
<th>ASTM Specification / Grade</th>
<th>A36-08</th>
<th>A572-50 Type 2</th>
<th>A709-50 Type 2</th>
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*... denotes no requirement(s)*

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</table>

**Why Multiple Grades?**

**Multi-Certification**

First Name: Doug

Last Name: Rees-Evans

Nicknames: "Reesy" (grade school)

You can call me:

- Doug
- Douglas
- Mr. Rees-Evans
- Reesy

Whatever you call me; does not change who I am.

Which name/title is used = f ( CONTEXT )

Whichever Grade is used = f ( CONTEXT )
Why Multiple Grades?

A. The difference is due to…..

• Different specification bodies
• Different products and/or product applications
• Cross adaption / adoption

• Same Material ⇒ Different Grade(s) / {Name(s)} “multi-certification”:
due to “Application Context”

Questions

✓ Iron – Steel: What is the Difference ?
✓ Why are there multiple Grades of Steel ? Isn’t steel, steel ?
➢ How can a mill control chemistry ? Isn’t it dependent upon what scrap is used ?
  o How does a mill control the properties of a steel product ?
• If I retest a product, will I get the same results as in the MTR?
**Steelmaking** Process Diagram

![Process Diagram](image)

Product Design consideration flow counter to the “Process Flow”

**Ironmaking**

**Blast Furnace**

**Purpose:** transformation (smelting) of iron oxides (ores) to metallic iron (Hot Metal / Pig Iron)

**Inputs** (charge): prepared Iron Ore, limestone, coke

**Process:**
- preheated air blow through alternating layers of charge materials
- Progressive reduction of iron oxides to metallic iron
  
  \[
  \begin{align*}
  Fe_2O_3 & \rightarrow FeO \\
  FeO & \rightarrow Fe (l)
  \end{align*}
  \]
- secondary reductions: \( SiO_2 \rightarrow Si, MnO \rightarrow Mn \)
- Liquid Iron dissolves carbon from coke

**Outputs:** Hot Metal / Pig Iron

- Typ: 3.5 – 4.5 wt% C, 1 wt% Mn, 1-2 wt% Si

**Important Historical Developments:**
- Antiquity: precursor = “Bloomery”
- Late 1300’s – mid 1400’s: beginning of ironmaking
- “Shaft” Blast Furnace blow by water driven wheel.
- 1768 - 1777: Watt Steam engine replaces water wheels
- 1780’s: use of coke rather than charcoal
- 1828: Neilson employs “Hot” blast (air preheated by waste off-gasses)
**Process Design**

**Chemistry Control**

**Oxygen Map of Iron and Steel Making**

- **High Oxygen Potential**
- **Low Oxygen Potential**
- **Oxidation Reactions**
- **Reduction Reactions**

**Iron Ore** ($Fe_3O_4, Fe_2O_3$)

30% O

**“Ironmaking”**

$C + O → CO$

$Fe_3O_4 → Fe_2O_3 → FeO → Fe (l)$

**“Steelmaking”**

$C + O → CO_2$

$Mn + O → MnO$

$Si + O → SiO_2$

$Al + O → Al_2O_3$

Tap O: depends on Tap C

Steelmaker controls Deoxidation via Alloying

Final O: depends on Deox. Level (typ 1-50 ppm)

Tap: Hot Metal / Pig Iron / Alt. Iron

1-5ppm O

Low vs. High Oxygen Potential

**“Alternate Iron”**

**Reduction of Iron Oxides to Metallic Iron**

**without melting (solid state)**

Direct Reduced Iron (DRI) – Hot Briquetted Iron (HBI) – Sponge Iron

Solid Metallic for use in Melting

**Alternative to Blast Furnace**

- Shorter furnace campaign cycles
- Can operate in an on/off manner
- Similar “chemistry” to Hot Metal / Pig Iron

**Example Processes:**

- Pre 1980’s: MIDREX / HYL Process / FINMET
- 1990’s: Iron Carbide (Nucor) / Iron Dynamics*
  
  *DRI melted in submerged Arc Furnace
- 2000’s: ITmk3 / Mesabi Iron Nuggets

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American Institute of Steel Construction  28
**Puddling**

Inputs (charge): Pig Iron, Heat (fuel – coke / coal)

Process:
- Pig iron melted in the hearth of a reverberatory furnace
- Liquid stirred with a pole to expose to air.
- "Pasty ball" removed from furnace and hammer/rolled to "squeeze-out" slag
- Dissolved C oxidizes (surface liquid) reducing carbon content. Liquid composition moves into $\gamma + L$ phase ("mushy" puddle).
- Dissolved Si, Mn oxidize (slag)
- Comes "of nature" when C & temp reaches $\gamma_{(solid)}$ phase.

Outputs: Wrought Iron
- Typ: 0.10 – 0.20 wt% C (max 0.05 – 0.25)
- Extremely variability in C content between "batches"
- Negligible Mn, Si

Important Historical Developments:
- 1613: Reverberatory Furnace Invented
- 1760: Puddling Process Invented
- 1890’s: Wrought Iron for structural applications largely replaced by steel
- 1925: Aston Process: Bessemer "iron" replaces pig iron + reverberatory furnaces route – Puddling OBSOLETE
- Last commercial production of "true" wrought iron: USA 1989; UK 1973

---

**Bessemer**

[1st "tonnage" Steelmaking]

Inputs: Hot Metal, Air

Process:
- Hot Metal teemed into converter
- Air (78% N$_2$, 21% O$_2$) blown (20psig) from bottom of vessel through Hot Metal.
- Preferential oxidation of dissolved elements:
  - Si, Mn $\rightarrow$ C $\rightarrow$ Fe
  - Temperature

Outputs: (liquid) Steel – carbon level controlled by duration of the "blow"

Advantages: (over Puddling)
- Speed: 20 tons in 30 mins vs ¾ tons in 4-6 hrs
- Autogenous: no external heat / energy required
- Cost: price of finished steel in 1865 (converted to 2010 USD).
  - Puddle Iron: $5,000/ton
  - Bessemer Steel: $800/ton

Difficulties:
- Cannot remove Sulfur nor Phosphorous (no slag)
- Process speed too rapid for real-time chemical analysis
- Cannot use scrap
One of the early MAJOR problems with implementation of the Bessemer Process was the inability to CONTROL SULFUR and PHOSPHOROUS.

1879: Thomas discovered that Sulfur and Phosphorous could removed from liquid steel by the use of “BASIC” slags and refractories.

ACID Slag / Refractory = Silicate (SiO₂) based.

BASIC Slag / Refractory = Lime (CaO₂) / Dolomitic (CaO₂, MgO) based.

* In Europe, due to high P-bearing ores, the “Basic” Bessemer Process was widely used. More commonly referred to as the “Thomas Process”.

* In NA, due to ores with lower P-content, and the higher cost of Basic refractories (at the time), the “Acid” Bessemer Process was more predominant.

Process Design

Refractories: Material(s) of very high melting point that are suitable for the use as linings for steel-making, handling, reacting, and transfer vessels.

eg: CaO, MgO, Al₂O₃, SiO₂, MnO

Slag: A mixture of non-metallics that is liquid at steelmaking temperatures.

- Lower density than steel (floats on top of steel).
- Capable of absorbing and retaining “impurities” (usually as oxides / sulfides) from liquid steel.
- Acts as a thermal blanket (reduces radiant temp loss from liq. Steel).
- Acts as a re-oxidation barrier (prevents direct air → liq. Steel contact).
- Chemical Equilibrium: steel ↔ Slag
  “don’t make steel – make slag”

* Sustainability:
  - Metallics recovered from used refractories and slag. Returned to melting processes.
  - Used refractories: crushed, classified – used as concrete aggregate, road-base, RR ballast, etc.
  - Used Slag: crushed, classified – used as concrete aggregate, road-base, RR ballast, etc.
STEELMAKING

Open Hearth
(Seismen’s Process)
Acid / Basic

**Inputs**: Hot Metal, Fuel, Air, Slag Formers, Scrap &/or Pig Iron

**Process**:
• Solids (scrap/Pig Iron) + slag formers charged
• Hot combustion product gases passed over top of slag and molten bath. Waste gases heat regeneration chambers for the preheating of combustion air
• When solids were molten, Hot Metal charged (teemed)
• Preferential oxidation of dissolved elements (refining): Si, Mn $\Rightarrow$ C

**Outputs**:
(liquid) Steel – carbon level controlled at tap by sampling

**Advantages**:
• Large heat size: 50 – 300 tons
• Process speed allows for chemical sampling
• S & P control
• Can charge solid Pig Iron and/or Scrap

**Difficulties**:
• Long process times (4-6 hrs).
• Needs Hot Metal source
• Needs fuel (Bessemer = autogenous).

STEELMAKING

Basic Oxygen Furnace

**Important Historical Developments**:
• ~1940 - 1945: “bulk” liquid Oxygen generation (Germany)
• 1949 - 1952: Development & Commercialization of LD/BOF (Voest-Alpine, Linz & Donawitz, Austria)
• 1954: 1st commercial US - BOF steelmaking (McLouth Steel)

**Inputs**:
• “Iron Units” - Scrap, Pig Iron, Alt. Iron, Hot Metal
• Slag Formers and Fluxes
• Energy$_{\text{chemical}}$ $\Rightarrow$ Supersonic O$_2$

**Process**:
Charge Solids $\Rightarrow$ Charge Hot Metal $\Rightarrow$ Blow $\Rightarrow$ Tap
Preferential oxidation of dissolved elements: Si, Mn $\Rightarrow$ C : Heat

**Outputs**:
(liquid) Steel

**Advantages**:
• Autogenous (requires no external energy source)
• Dilution of “residual” elements

**Difficulties**:
• Requires continual Hot Metal supply
**Electric Arc Furnace**

**Important Historical Developments:**
- 1808: Carbon Arc discovered (Humphrey Davy)
- 1899: 1st commercial EAF steelmaking in Le Praz, France
- 1909: 1st commercial US EAF steelmaking (US Steel – Southworks, Chicago, IL)

Many different styles and configurations of EAFs
Many different methods and mode of EAF practice/operation

**Inputs:**
- “Iron Units” - Scrap, Pig Iron, Alt. Iron, Hot Metal
- Slag Formers and Fluxes

**Process:**
- Charge → Melt → Refine → Tap
- Desired chemistry (C) & temperature

**Outputs:** (liquid) Steel

**Advantages:**
- Flexibility - charge materials (variety, not reliant upon constant source of Hot Metal)
- Operations: On/Off quickly

**Difficulties:**
- Non-autogenous
- “Residual” element control (“high” scrap content in feed stock)

**Heat Size:** 30 – 400 ton
**Tap-Tap:** 30min – 1 ½ hr
**(assuming 80 – 180 heat size)**

**Domestic Use**
- 1865 - 1966
- 1870 - 1967
- 1909 - current
- 1954 - current

**“Metallics” Input to Furnace**

**Metal Source(s)**

**Domestic Use**
- 1865 - 1966
- 1870 - 1967
- 1909 - current
- 1954 - current
Scrap Selection

“graded” and segregated by: size, source (past history), expected chemistry

Blended into charge:
- Cost
- Density
- Melting Efficiency
  - yield
  - melting characteristics
- Chemistry
  - Chemical Energy
  - Residual Elements (Cu, Ni, Cr, Mo, Sn)

How can a mill control chemistry? Isn’t it dependent upon what scrap is used?

A.
- Scrap has had a long history of use in steelmaking
  - Open Hearth (1860 – 2001)
  - Basic Oxygen (1952 – current)
  - Electric Arc (1909 – current)
- Careful selection and blending of Scrap
  - Chemistry (inc. anticipated “residual” content) (Grade Requirements)
  - Melting Characteristics
  - Cost
- Dilution
How can a mill control chemistry? Isn’t it dependent upon what scrap is used?

- Chemistry = more than just scrap
- Why is Chemistry important?

Product Mechanical Properties (MP)
- Strength (Yield, Tensile)
- Elongation
- Impact Resistance
- Weldability
- Hardness / Wear-resistance
- Etc...

\( MP = f(\text{chemistry}, \text{microstructure}) \)

Re-defined question:

How does a mill control the properties of a steel product?

Process Design Influences

1. Steelmaker decides:
   - What product(s)
   - Target Market
   - Where

2. External Influences:
   - Product “demands”
     - Requirements / limitations
   - Available Technology(s)
   - Raw Material
     - Cost / Availability / Suitability
   - CO2$ !

\[ 1 + 2 \rightarrow \text{which technology solution to employ} \]
During "Steelmaking"
- $C + \frac{1}{2}O_2 \rightarrow CO$
- $Mn + O \rightarrow MnO$
- $Si + O_2 \rightarrow SiO_2$

Desirable elements removed

"Secondary Steelmaking"
- Tailor to desired chemistry

"Types" of Elements

- **Oxidizable Elements**
  - can be removed from liquid steel by adding Oxygen (O)
    - Aluminum (Al) and Titanium (Ti)
    - Silicon (Si) and Vanadium (V)
    - Carbon (C) and Phosphorous (P)
    - Manganese (Mn) and Iron (Fe)

  - Order of Removal
    - "lost" during Melting Operations

- **Reducible Elements**
  - can be removed from liquid steel by removing Oxygen (O)
    - Sulfur (S)
    - Oxygen can be removed from steel by adding oxidizable elements
      - Most commonly Si, Al, Mn, C
“Types” of Elements

- **Other Elements**
  - cannot be removed from steel by adding or removing Oxygen (O)
  - Level controlled by dilution (adding clean material) (scrap or iron product)
    - Copper (Cu)
    - Chrome (Cr)
    - Nickel (Ni)
    - Molybdenum (Mo)
    - Tin (Sn)
    - *Antimony (Sb)
    - *Arsenic (As)
      - * commonly a residual from iron ores.
  - When purposefully added, known as: Alloying Elements
  - When arriving from raw material stream (eg. Scrap, Ore), Known as : Residual Elements

Secondary Steelmaking

- **Desulfurization** (slag treatment)
- **Build Chemistry**
  - (add elements to obtain desired chemistry – C, Mn, Si, Al, Cu, Ni, Cr, V, Nb, etc.)
- **Inclusion Control** (deox / deS products)
- **Temperature Control**
  - (casting consideration, segregation)
- **Homogeneity**
  - (chemistry, temperature)
- **Degassing** (DH, RH, Tank, etc…)
  - Control level of dissolved gasses
    - H, O, N
Mechanical Properties

\[ MP = f(\text{chemistry, microstructure}) \]

How Does Chemistry Influence Mechanical Properties?

Strengthening Mechanisms

- Solution Strengthening
- Precipitation / Dispersion Strengthening

Contribute collectively to observed mechanical properties

Metal Theory

Crystal Defects

A: Interstitial Solute
Solute atom does not occupy lattice position of solvent (solid-state diffusion via interstitial pathways)

B: Substitution Solute
Solute atom occupies lattice position of solvent (solid-state diffusion via vacancy migration)

C: Edge Dislocation
An extra partial plane of atoms within the lattice. Local lattice is distorted/stretched at edge of dislocation.

D: Vacancy
An unoccupied lattice location
Dislocation Slip

**Dislocations** (may be “Edge” or “Screw”)

AN EXTRA PARTIAL PLANE OF ATOMS WITHIN THE LATTICE  
Local lattice is distorted/stretched at edge of dislocation.

Plastic Deformation = Dislocation Slip

- When under stress, dislocations break existing bonds with neighbors and re-establish bonds with other neighbors. May progress rapidly through crystal.
- Net effect, the dislocation plane moves through the bulk crystal and shape has permanently changed.
- Stress required to slip dislocations is on the order of \( x10^2 \text{ less} \) than is required to cause slip of entire (full) plane of atoms. Permanent Shape Change.

Crystal Anisotropy

within the 3-D crystal unit cell / lattice there are planes with differing atoms “packing” efficiencies.

(100) Plane in BCC Iron  
Easy slip ⇒ “Weak”

(111) Plane in BCC Iron  
Difficult slip ⇒ “Strong”

Different planes offer different resistances to dislocation motion

@ Grain Level:  
Steel = ANISOTROPIC

@ Macro Level:  
randomly oriented grains exhibit “average” behavior
**Solution Strengthening**

- Unless involved in forming a precipitate or other phase, all alloying element atoms will occupy either an Interstitial or Substitution Position within the lattice.
- Presence of solute atoms create a “localized” strain on the iron lattice.
- Interstitial solutes (low concentrations) can “Pin” dislocations. (Increases strength)
- Substitution solutes interfere with / block dislocation slip. (Increases strength)
- For Substitution Elements with atomic diameters greater than iron: Strengthening Effect increase with increasing atomic diameter.

**Solid State Diffusion**

- Given sufficient time and energy (temperature), solute atoms can diffuse through the crystal
  - **Interstitial Solute**: diffuse through interstitial “pathways” between iron atoms.
  - **Substitutional Solute**: diffuse via “Vacancy Migration”

“red” atom “breaks” bond with neighbor, moves one atomic unit left and re-establishes bonds. Net effect: Vacancy Migration to the right.
Mechanical Properties

$$MP = f(\text{chemistry, microstructure})$$

How Does Microstructure Influence Mechanical Properties?

Strengthening Mechanisms
- Solution Strengthening
- Precipitation / Dispersion Strengthening

Contribute collectively to observed mechanical properties

Grain Boundaries

- Grain Boundaries =
  intersection of lattices differing in orientation (random)
- Mismatch = strained lattice = un-satisfied bonds
  Grain Boundaries = high potential chemical energy

“NATURE TENDS TO THE LOWEST ENERGY STATE”

In a fixed volume:
- Small grains = more grain boundaries
- Large grains = more grain volume
- Large grains = lower overall energy

Given the impetus (temperature + time); large grains will grow larger by consuming smaller grains.

- Dislocation and Vacancies do not cross, but “pile-up” at Grain Boundaries.
  - Larger grains offer more unimpeded volume for dislocation to move with.
  - Smaller (finer) grain size = stronger.
Purpose:
• Transformation a solid cast shape into a desired "finished product" shape/form
• Product possesses desired mechanical properties/characteristics

Process:
• Material is plastically deformed by passing between counter-rotating rolls
  • In Austenitic Temp range << Hot Rolling >>
  • In Ferritic Temp range << Cold Rolling >>

• Myriad of Roll shapes, sizes, and configurations.
  • \( f \text{(product shape, as-cast size / shape)} \)

Important Historical Developments:
• 1590: 1st slitting and cutting of cast iron bar (by rolls) for nail mfg.

Grain Size Control:
• Ideal Grain shape: Equiaxed
• Plastically deformed austenitic grains will re-crystallize
• Austenitic Temperature range, given time: grain coarsening
### Grain Size Control

#### Hot Rolling

**Austenite ⇄ Ferrite Transformation:**
- Ferrite nucleates at defects in Austenite (grain boundaries, precipitates, second phases)

**Greater reduction ⇄ Finer recrystallized grains**

**Fine Austenite Grain Size ⇄ Fine Ferrite Grain Size**

#### Process Design

**Microstructure**

### Grain Size Control

**Theoretical shape attributes • Hypothetical mill • Grade: A992**

<table>
<thead>
<tr>
<th>Measured Property</th>
<th>W16x36</th>
<th>W14x398</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness (in)</td>
<td>.430</td>
<td>2.845</td>
</tr>
<tr>
<td>Chemistry (wt%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>.08 - .12</td>
<td>.08 - .12</td>
</tr>
<tr>
<td>Mn</td>
<td>.80 - .90</td>
<td>1.20 - 1.30</td>
</tr>
<tr>
<td>V</td>
<td>.01 - .02</td>
<td>.05 - .06</td>
</tr>
<tr>
<td>Strength (ksi)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yield</td>
<td>60 - 65</td>
<td>50 - 55</td>
</tr>
<tr>
<td>Tensile</td>
<td>75 - 80</td>
<td>65 - 70</td>
</tr>
<tr>
<td>fy/fu</td>
<td>.75 - .80</td>
<td>.80 - .85</td>
</tr>
<tr>
<td><strong>Grain Size</strong></td>
<td>9 – 10</td>
<td>5 - 6</td>
</tr>
</tbody>
</table>

*Fine*: recrystallized grain size

*Coarse*: recrystallized grain size

---

*Actual analysis and properties will vary from mill to mill.*
Precipitation Strengthening

**Precipitates** form, upon cooling / during transformation from a supersaturated solid solution.

- Fine particles or second phase
  - **Carbides**
    - Fine particles: VC, Nb,C , TiC ,
    - Second Phase: Fe3C (Cementite: laths as part of pearlite)
  - **Nitrates**
    - Fine particles: VN, NbN, AlN, TiN,
  - **Carbonitrides**
    - Some elements will form both carbides and nitrates which are mutually soluble (C,N).
      - Fine particles: V(C,N), Nb(C,N)
  - **Strengthening Mechanism(s):**
    - γ → α nucleation site – promotes fine α grain size
    - “macro” block to dislocation
Mechanical Response

Young's / Elastic Modulus

{ Ferritic State }

"constant" characteristic of a polycrystalline metal

Governed by inter-atomic binding forces

NOT ALTERED unless basic nature of metal is changed

Eg. Add enough alloy to become something different:

\[ Ni + Cr + Fe \Rightarrow \text{stainless steel}; \]

Carbon steels: NOT SENSITIVE TO STRUCTURE

Unaffected by Grain Size / Alloy content

** ISOTROPIC BEHAVIOR **

<< same mechanical behavior regardless of direction >>

Important when yielding is a design consideration

Temperature Dependent

Mechanical Response

Yield

Point / Strength / (Lüder’s) Plateau

Elastic behavior ends and yielding begins when sufficient stress is applied to result in "sudden":

• dislocation slip along "weak" crystal axes
• creation of new dislocations

Interstitial Solutes (C,N) pinning dislocations, preventing slip.

"sharp" Yield Point: present in lower strength steels (lower C, N concentrations) = activation energy to un-pin dislocations and allow slip.

strain rate sensitive. \( \partial \text{ Strain Rate} = \partial \text{ Yield Point} \)

Yield (Lüder’s) Plateau: stress level required for plastic deformation (un-pinned dislocations = weak axes). Due slip in randomly oriented grains (polycrystalline) = "plateau" is not a "unique" stress level.

Yield Strength: If no sharp point, virtually impossible to determine exact point when plastic deformation occurs; Yield Strength = occurs at .2% deformation (offset from elastic modulus).
As dislocations slip through the grains, they will encounter:

- Grain Boundaries
- Substitution Solute Elements
- Precipitates, Second Phases, Inclusions

1. Dislocations will accumulate at Grain Boundaries and Precipitates, Second Phases, & Inclusions
   
   Increasing Stress required to create new dislocations and slip on multiple crystal “packing” axes (not only the weak axis)

2. Dislocations pinned by solute atoms
   
   Uniform Cross-Sectional Volume Reduction / Elongation

Ultimate Tensile Strength

Maximum stress that the material can bear without the onset of non-uniform elongation across the member.

Accumulation of many multiple dislocations at Grain Boundaries and Precipitates, Second Phases, & Inclusions ultimately lead to microscopic cracking.

- Reduction of stress carrying cross-section
- Localized Plastic Deformation (necking)
- Coalescence of micro-cracks accelerates necking
- Granular Cleavage

ultimately leads to Fracture
**Mechanical Response**

**Alloying Content (C)**

- **Eutectic C:** 100% Pearlite
  - Strong (if no Cementite)
  - Very poor ductility / elongation
    - Ductility due to ferrite
  - *Eg: T-Rail, bearing*

- **Ferrite & Cementite contributions**
  - Stronger
    - Interstitial Strength
    - Cementite
  - Reduction in vol% of Ferrite = reduced ductility
  - Pearlite lath spacing has moderate influence

- **Low C:** 0 Ferrite, 0 Pearlite
  - Weak (if no YS / UTS)
  - Ductile (if elongation)

**Carbon Steel Microstructure:**

- Ferrite : (.02%C), Ductile, Weak
- Pearlite : laths (Ferrite, Cementite)
- Cementite : (6.67%C), Brittle, Strong

**Ferrite Governs**

- Reduction in vol% of Ferrite = reduced ductility

**How does a mill control the properties of a steel product?**

- varying degrees of control on process variables
- an improvement in one property can not be made without influence upon other properties
- seek to optimize ‘total package’ of properties in a **cost** effective manner to meet grade requirements.
Questions

✓ Iron – Steel: What is the Difference?
✓ Why are there multiple Grades of Steel? Isn’t steel, steel?
✓ How can a mill control chemistry? Isn’t it dependent upon what scrap is used?
  ✓ How does a mill control the properties of a steel product?
➢ If I retest a product, will I get the same results as in the MTR (Mill Test Report)?

If I retest a product, will I get the same results as in the MTR?

A. (short Answer)
  • Exactly Same Values?
    ✗ No
  • “Nominally” Same Values?
    ✓ Yes
Chemical Analysis

Casting Method(s) strongly influence variability in “Product Check”

<table>
<thead>
<tr>
<th>Ingot Casting</th>
<th>Continuous Cast</th>
</tr>
</thead>
<tbody>
<tr>
<td>Killed Nature</td>
<td>Unkilled - fully killed</td>
</tr>
<tr>
<td>Rimming &amp; Capped</td>
<td>CO evolution (local changes in C levels)</td>
</tr>
<tr>
<td>Solidification Rate</td>
<td>SLOW</td>
</tr>
<tr>
<td>(8 hrs - 2 days)</td>
<td>46 - 60 min</td>
</tr>
<tr>
<td>10 - 40 tons</td>
<td>80 - 120 tons</td>
</tr>
<tr>
<td>Segregation</td>
<td>can be significant (C, S, P)</td>
</tr>
<tr>
<td>“Heat”/Batch Separation</td>
<td>Single Heat in Mold</td>
</tr>
</tbody>
</table>

General Metallurgy

“Soda” Analogy

“green caffeine” (l) + CO₂ (g) → CO₂ (g) removed from system (degassed)

Δ vol. → loss of CO₂ solubility

Ingot Casting

Killed | Semi-Killed | Capped | Rimmed

“Killed”

- dissolved oxygen content low enough to prevent CO₂ evolution during solidification.
- “Killing” accomplished by removing / “tying-up” dissolved oxygen through reaction with metals possessing a high chemical affinity for oxygen.

2Al + 3O = Al₂O₃ (s) | Si + 2O = SiO₂ (s)

“Gross” gas evolution during solidification
General Metallurgy

“Segregation”

In alloy systems, during solidification, the higher melting point constituent(s) freeze first. (Slow cooling):
• Lower melting point constituent(s) will be "rejected" by the advancing solidification front.
• Remaining liquid becomes enriched in lower melting point constituents.
• Upon complete solidification: **Regions of "Composition Fluctuation" ≠ SEGREGATION** << different chemistry in different regions >>

**Analogous Example**: Traffic Jam = Solidified Alloy. (Cars = Iron Atoms, Motorcycles = Sulfur Atoms)

Fast Cooling: Low (microscopic) Segregation
Chemically Homogeneous

Slow Cooling: High (macroscopic) Segregation
Chemically Inhomogeneous

---

MTR Variability

Chemical Analysis

**Sequence (Continuous) Casting**

1. Heat “1” (chemistry “1”) teemed from ladle [A] to tundish [B]. Tundish distributes steel to casting mold(s) [C].
2. When ladle is empty, ladle removed. Tundish retrains steel of Heat “1”.
3. new ladle of Heat “2” (chemistry “2”) substituted, and teemed to tundish.
4. For period of time, tundish chemistry = decreasing % of Heat “1” and increasing % of Heat “2”; after which chemistry = Heat “2”
5. When ladle “2” is empty, steps 3 & 4 repeated

**Product of Heat “2” will possess a changing mix of Chem “1” to Chem “2” on one end, a changing mix of Chem “2” to Chem “3” on the other, and chem “2” throughout the “middle”**

- Heats 1, 2, 3 must be of nominally same chemistry (Grade Separation)
- Compliance to spec: eg. ASTM A6 Table A – Permitted Variations in Product Analysis
- ‘MTR’ Chemistry = average of samples taken during casting of the Heat
Tension Test Results

Appendix X2. Variation of Tensile Properties in Plates and Shapes

X2.1

- "tension testing requirements ... are intended only to characterize the tensile properties of a heat of steel ...".
- "not intended to define ... tensile properties at all possible test locations ..."
- "it is well known and documented that tensile properties will vary within a heat or individual piece of steel as a function of chemical composition, processing, testing procedure and other factors."
- "incumbent on designer and engineers to use sound engineering judgment when using tension test results shown in mill test reports."

X2.2

- Expected variability: “one standard deviation equals approximately 4% of required tensile strength, 8% of required yield strength, and 3% of required elongation.”.

X2.1 : “testing procedures ... Have been found to provide structural products adequate for normal structural design criteria.”

“Thick” W Shapes

Residual Heat: variable thermal profile across thickness
- leads to variable grain size across thickness (grain growth)

Region of low reduction ratio
- coarse grain size

Region of potential high segregation {C, S, P} (ingot cast)
- S,P dramatically reduces strength, elongation toughness

Core Area (thickness: ASTM: + 1 ½”; AISC: +2”)
- Coarest Grain Size / potentially most segregated
- Lowest Toughness
Coupon Type / Location

ASTM A6/A6M -10a

Mill Testing (MTR Values) use:
- $\frac{1}{3}$ of the way from the flange centerline to the flange toe
- Full thickness
- 8" gage
- ASTM A370 – 1½" Wide "Plate-Type" Coupon (Fig 3)

MTR Variability

1/3
2/3

Full Thickness Plate Specimen (MTR)
- Average of "discrete point" strength(s) across flange thickness
- Expected in-service response

0.500" Round Coupon
- "localized properties"
- ≠ Plate Specimen values
- ∆ microstructural, chemical differences
- Difference exaggerated by
  - thickness
  - QST (A913) / surface treatment / case hardening

2" gage length coupon gives better % (more) elongation vs. 8" gage
If I retest a product, will I get the same results as in the MTR?

A. (Long Answer)
   • Exactly Same Values?  
     × No
   • “Nominally” Same Values?  
     ✓ Yes – within allowable variations
     o Mech. Prop’s: Same coupon and location(s)

Questions

✓ Iron – Steel: What is the Difference?
✓ Why are there multiple Grades of Steel? Isn’t steel, steel?
✓ How can a mill control chemistry? Isn’t it dependent upon what scrap is used?
   ✓ How does a mill control the properties of a steel product?
✓ If I retest a product, will I get the same results as in the MTR?
For more information or answers to other Steel questions contact:

AISC Steel Solutions Center
866.ASK.AISC (866-275-2472)
solutions@aisc.org.

THERE’S ALWAYS A SOLUTION IN STEEL

CEU/PDH Certificates
Within 1 business day…

• You will receive an email on how to report attendance from: steel@wyndhamjade.com.

• Be on the lookout: Check your spam filter and junk folder!

• Completely fill out online form. Don’t forget to check the boxes next to each attendee’s name!

• OR…
CEU/PDH Certificates
Access available in 24 hours…

• Go to:
  http://www.wyniade.com/aiscfall11/webinarCEU.
  Username: Your Web ID (found on your registration receipt)
  Password: Your Last Name

• Completely fill out online form. Don’t forget to check the boxes
  next to each attendee’s name!

• Questions? Please email us at webinars@aisc.org.

AISC Seminars

Fall Schedule has started!
22 cities, 4 different seminars including

[www.aisc.org/seminars](http://www.aisc.org/seminars)
AISC Steel Camp

2 day, 4 topics, 15 hours of Continuing Education,
One low price.
Charlotte, NC – October 6,7

www.aisc.org/steelcamp

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Thank You!