AISC Live Webinars

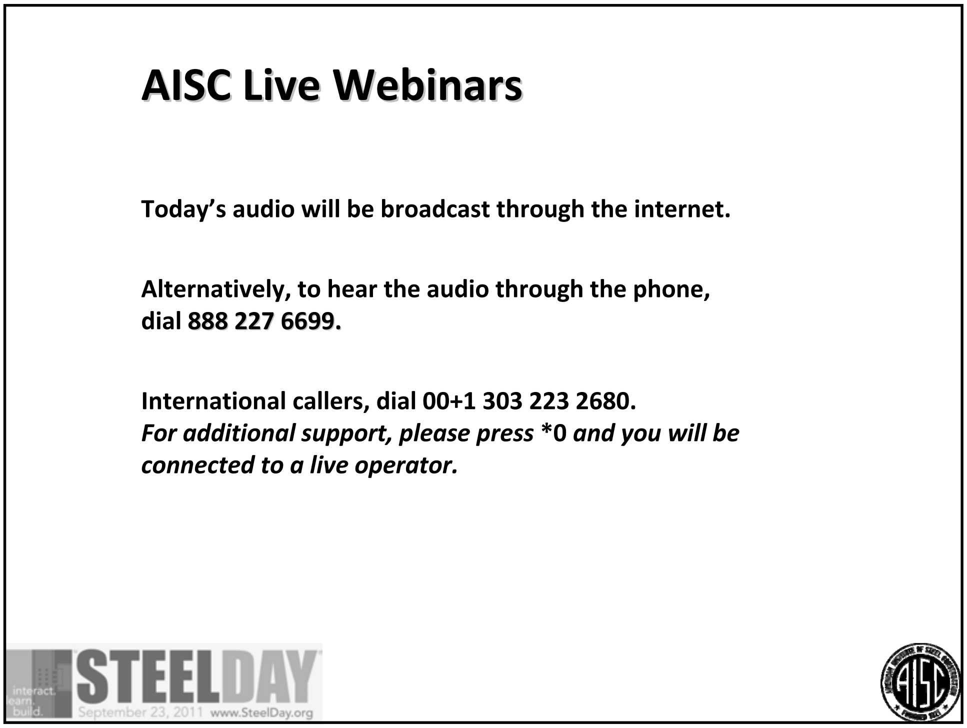
Thank you for joining our live webinar today.
We will begin shortly. Please standby.

Thank you.

Need Help?
Call ReadyTalk Support: 800.843.9166

There's always a solution in steel.

interact. learn. build. STEELDAY
September 23, 2011 www.SteelDay.org



AISC Live Webinars

Today's audio will be broadcast through the internet.

Alternatively, to hear the audio through the phone, dial 888 227 6699.

International callers, dial 00+1 303 223 2680.
For additional support, please press* *0 *and you will be connected to a live operator.

interact. learn. build. STEELDAY
September 23, 2011 www.SteelDay.org

AISC Live Webinars

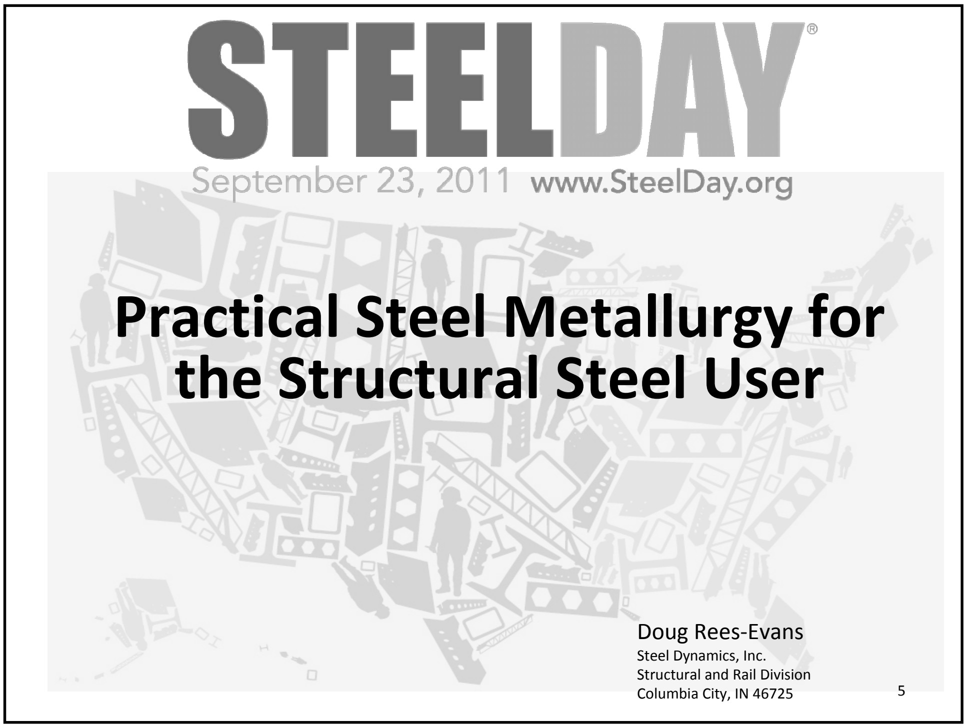
Today's live webinar will begin shortly.
Please standby.
As a reminder, all lines have been muted. Please type any questions or comments through the Chat feature on the left portion of your screen.

Today's audio will be broadcast through the internet.
Alternatively, to hear the audio through the phone, dial
888 227 6699.
International callers, dial **00+1 303 223 2680.**
For additional support, please press *0 *and you will be connected to a live operator.*

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

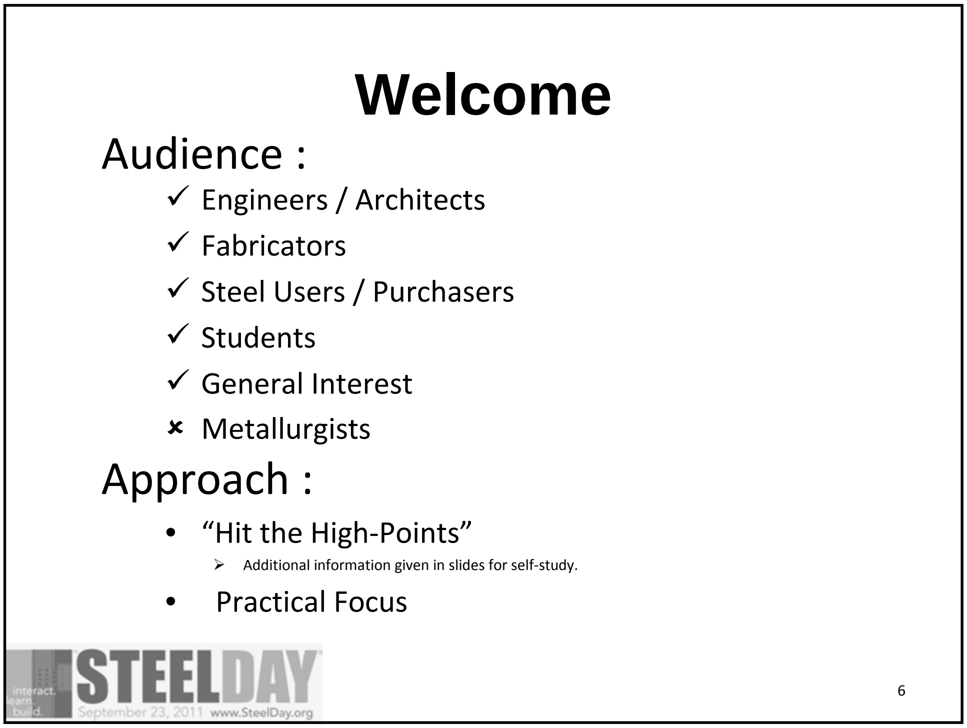


STEELDAY®

September 23, 2011 www.SteelDay.org

Practical Steel Metallurgy for the Structural Steel User

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

interact. learn. build. STEELDAY September 23, 2011 www.SteelDay.org

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?

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

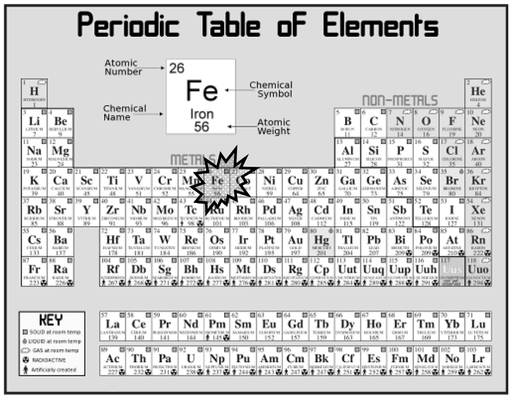
Our discussion will be limited to Carbon-Steels

Aka:

- *Carbon steel*
  - *Mild Steel (%C ≤ .25%)*
  - *Medium Carbon Steel (.25% > %C ≥ .45%)*
  - *High Carbon Steel (.45% > %C ≥ 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 ?

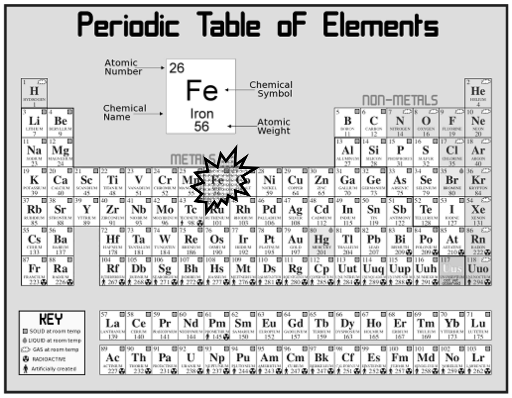
Iron



- 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 ⟵ Ironmaking
  - 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 ?

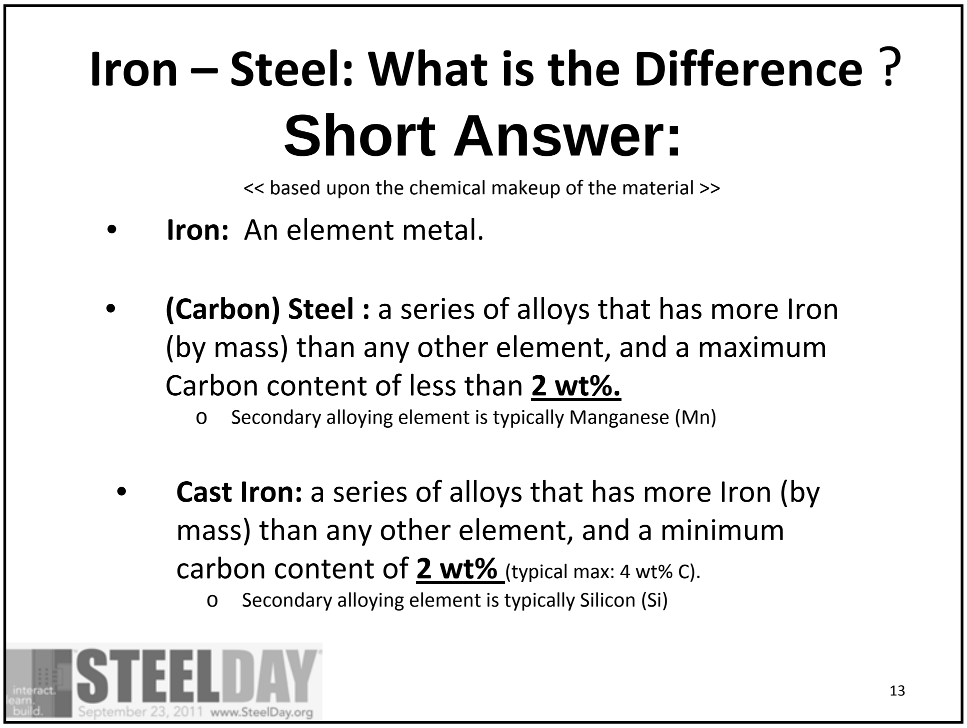
Iron-based Building Materials

26
Fe
Iron
56

- 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**

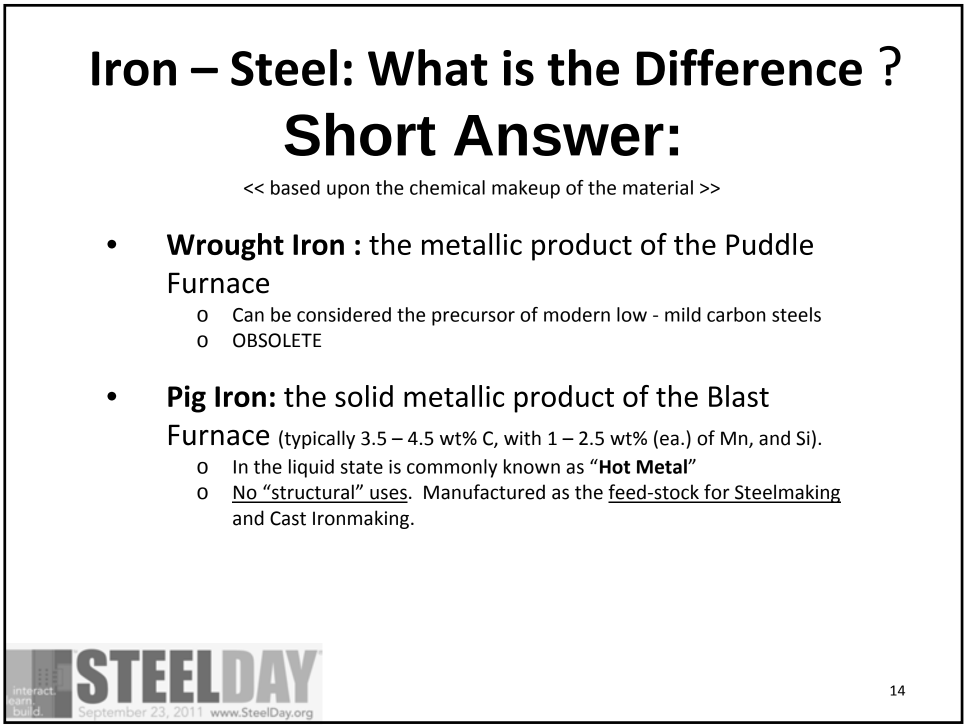


Iron – Steel: What is the Difference ?

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 ?

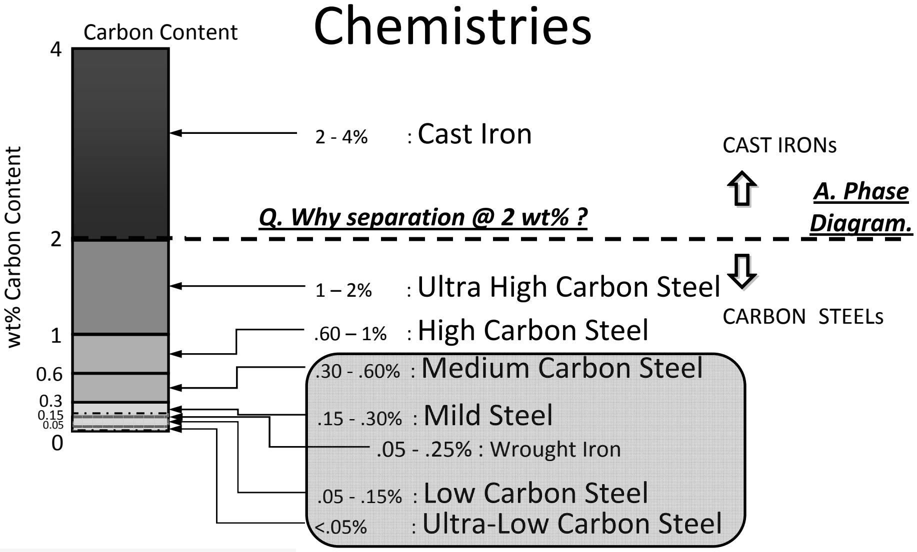
Short Answer:

<< 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



2 - 4% : Cast Iron

CAST IRONs

Q. Why separation @ 2 wt% ?

A. Phase Diagram.

1 – 2% : Ultra High Carbon Steel

CARBON STEELs

.60 – 1% : High Carbon Steel

.30 - .60% : Medium Carbon Steel

.15 - .30% : Mild Steel

.05 - .25% : Wrought Iron

.05 - .15% : Low Carbon Steel

<.05% : Ultra-Low Carbon Steel

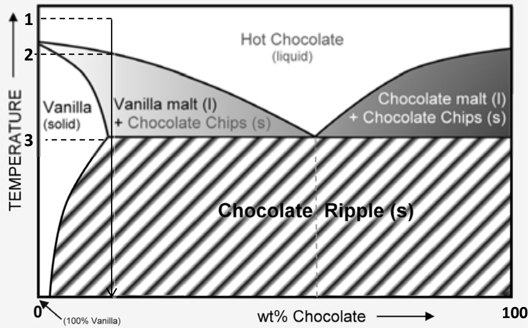
Common Structural Applications: Shapes, Bars, Bolts, Plates, etc.

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.}



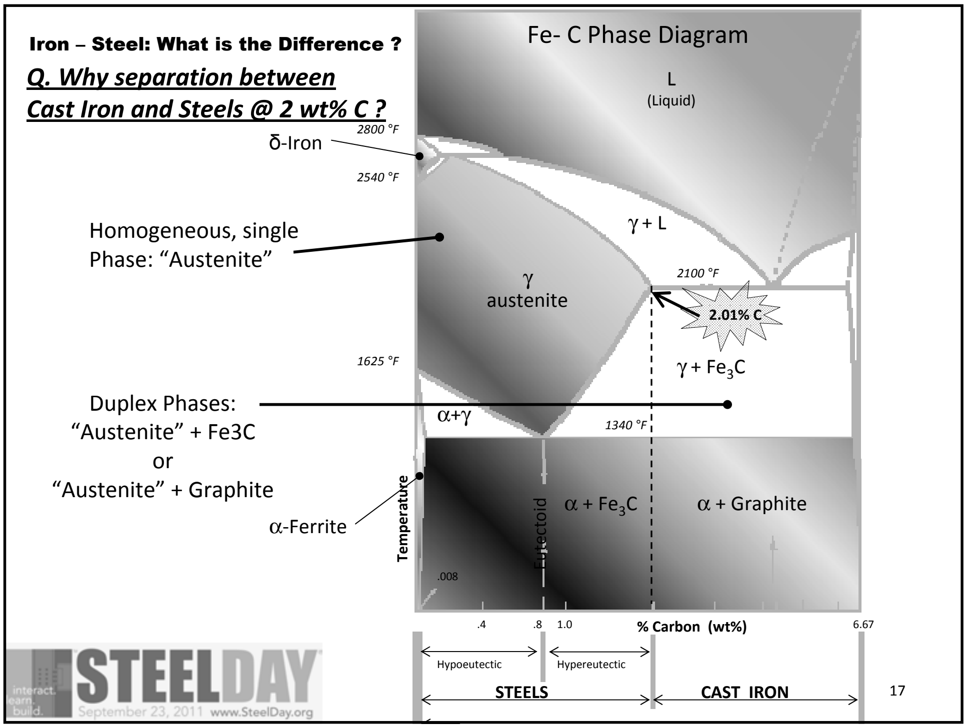
Example:

Hypothetical Chocolate- Vanilla Phase Diagram

Cooling of a composition (green arrow)

- Temp 1: Homogeneous Liquid (HC)
- 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 ?

δ-Iron

Homogeneous, single Phase: "Austenite"

Duplex Phases:
"Austenite" + Fe3C
or
"Austenite" + Graphite

α-Ferrite

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.

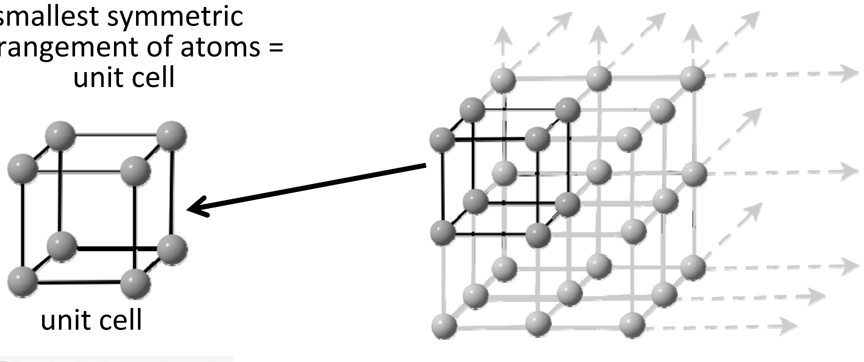
Allotropic = Has different crystal structures at different temperatures.

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



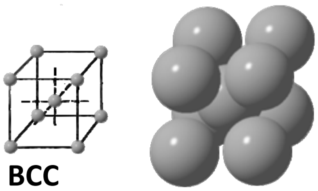
unit cell

crystal lattice

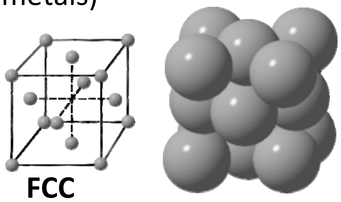
Basic Metallurgy

Crystal Space Lattices

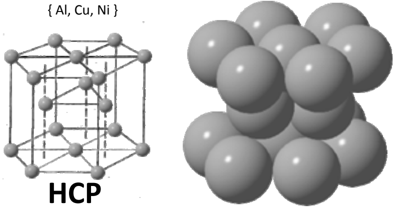
- **14 different types of crystal "space lattices".**
- 3 most common (favored by metals)



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



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

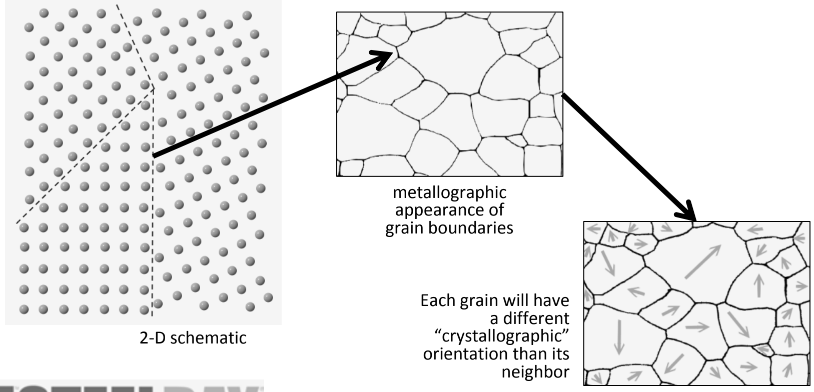


HCP
Hexagonal Close-Packed
{ Co, Ti }

Basic Metallurgy

Nature of Metals

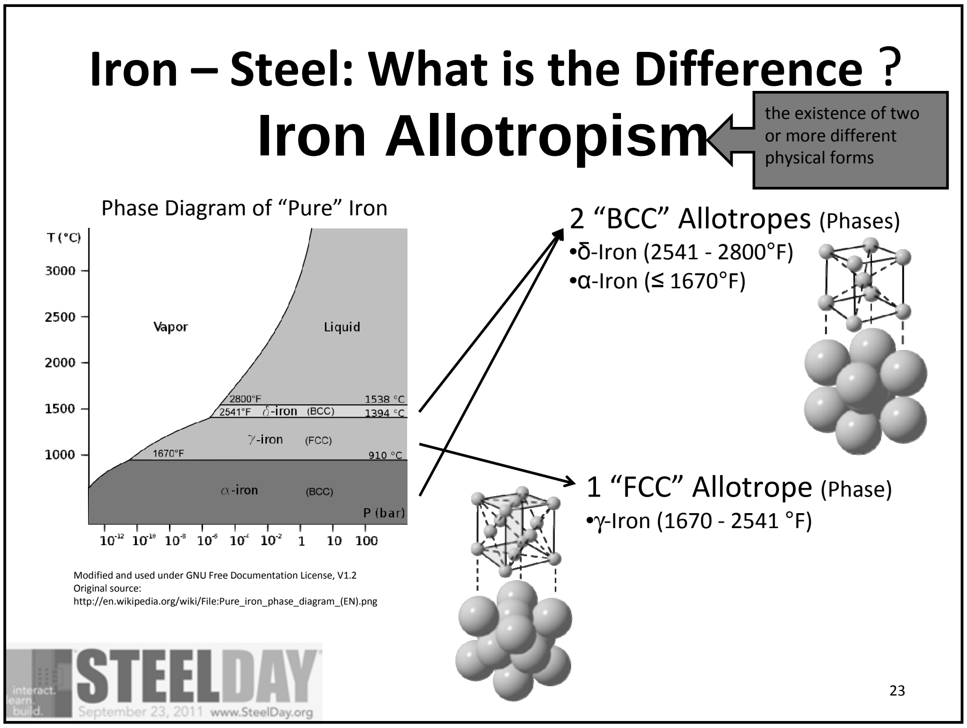
- intersection of crystal lattices of differing spatial orientations create grain boundaries



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

the existence of two or more different physical forms

Phase Diagram of “Pure” Iron

Modified and used under GNU Free Documentation License, V1.2
Original source:
http://en.wikipedia.org/wiki/File:Pure_iron_phase_diagram_(EN).png

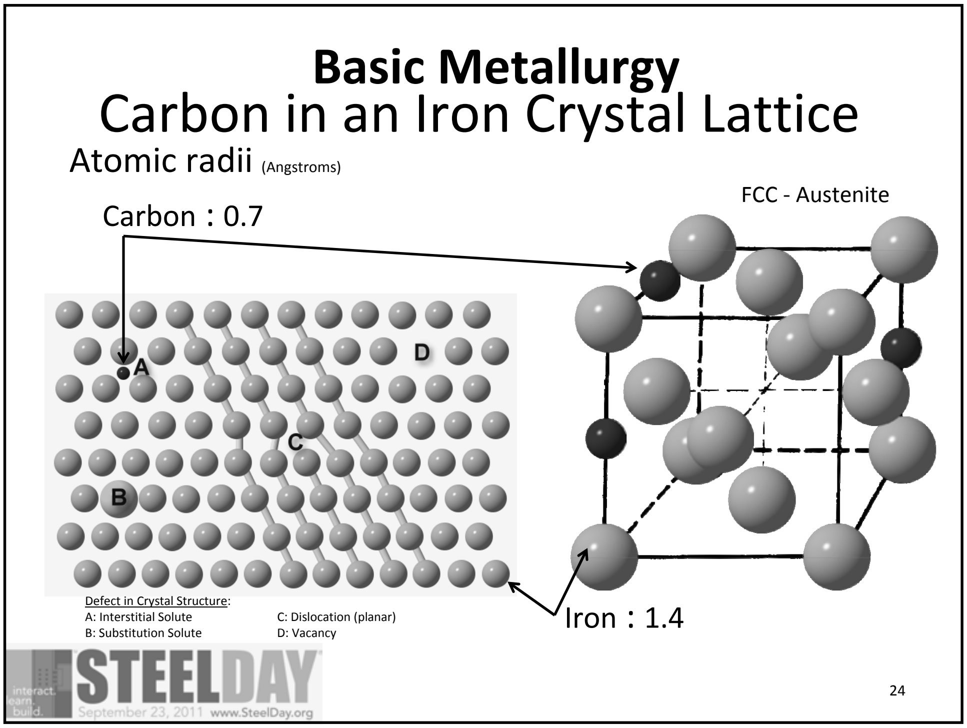
2 “BCC” Allotropes (Phases)

- δ-Iron (2541 - 2800°F)
- α-Iron (≤ 1670°F)

1 “FCC” Allotrope (Phase)

- γ-Iron (1670 - 2541 °F)

23



Basic Metallurgy

Carbon in an Iron Crystal Lattice

Atomic radii (Angstroms)

Carbon : 0.7

FCC - Austenite

Defect in Crystal Structure:

A: Interstitial Solute

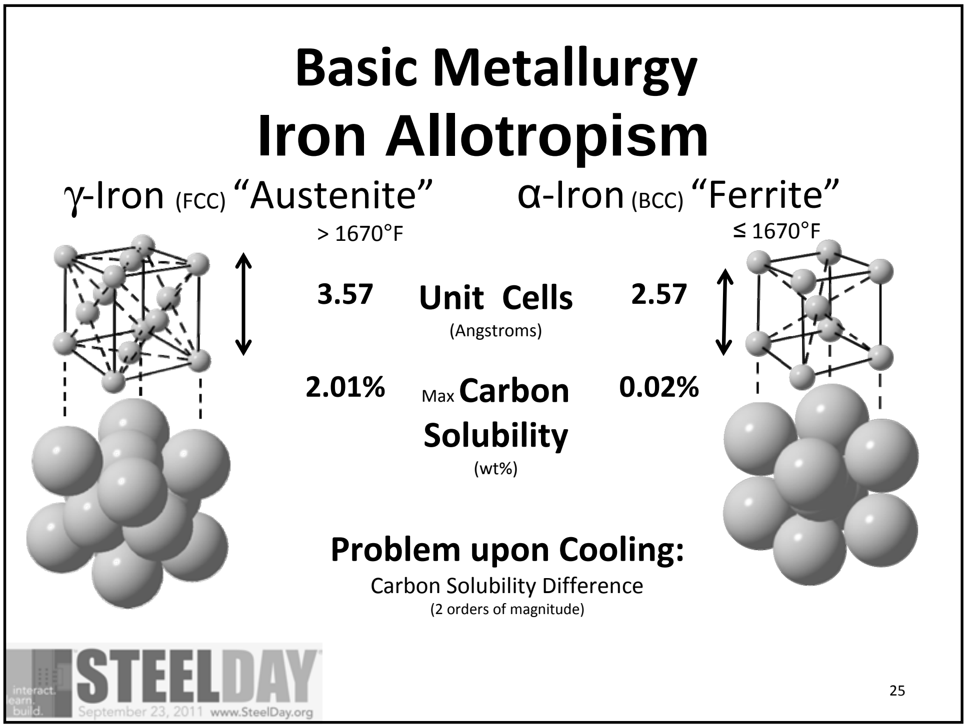
B: Substitution Solute

C: Dislocation (planar)

D: Vacancy

Iron : 1.4

24



Basic Metallurgy
Iron Allotropism

γ-Iron (FCC) "Austenite" α-Iron (BCC) "Ferrite"

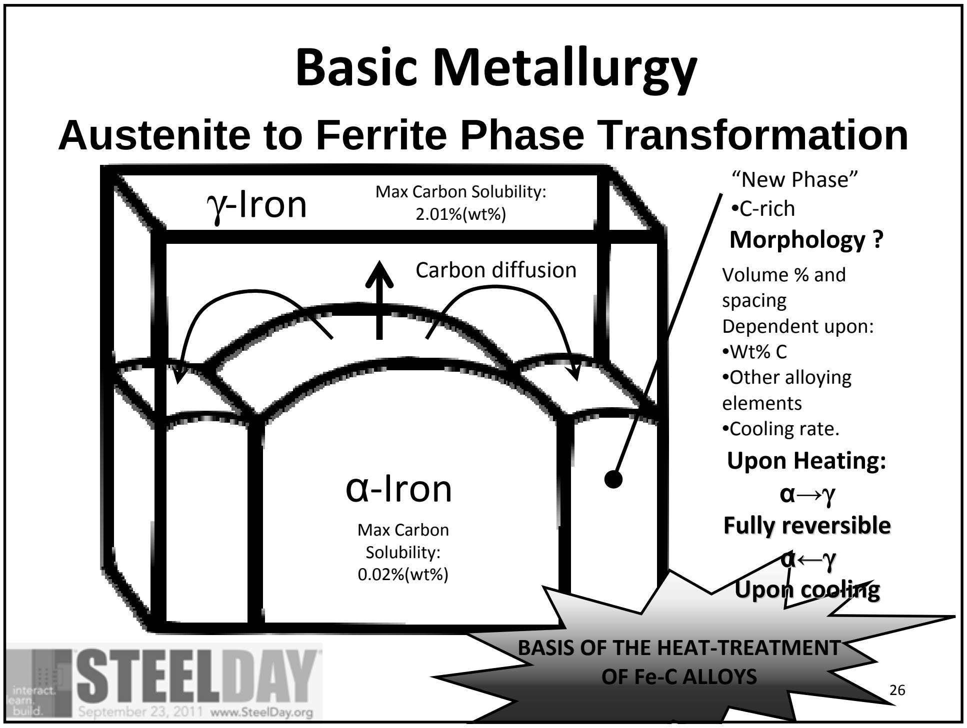
> 1670°F ≤ 1670°F

γ-Iron		α-Iron
3.57	**Unit Cells** (Angstroms)	2.57
2.01%	Max **Carbon Solubility** (wt%)	0.02%

Problem upon Cooling:

Carbon Solubility Difference

(2 orders of magnitude)



Basic Metallurgy
Austenite to Ferrite Phase Transformation

"New Phase"
- C-rich

Morphology ?

Volume % and spacing Dependent upon:
- Wt% C
- Other alloying elements
- Cooling rate.

Upon Heating:

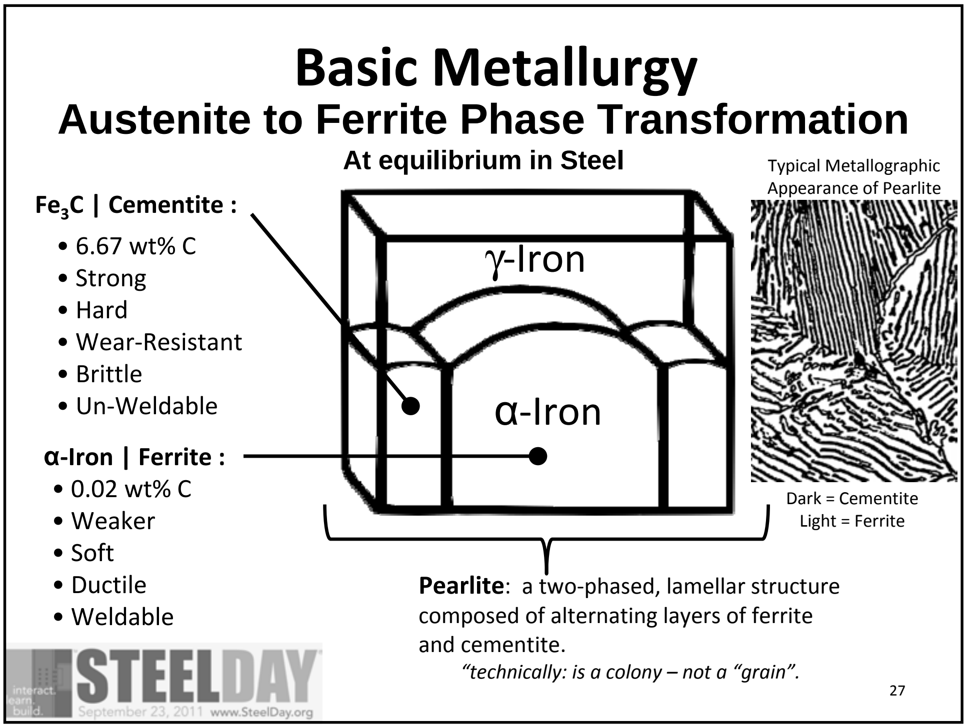
α→γ

Fully reversible

α←γ

Upon cooling

BASIS OF THE HEAT-TREATMENT OF Fe-C ALLOYS



Basic Metallurgy

Austenite to Ferrite Phase Transformation

At equilibrium in Steel

Fe_3C | Cementite :

- 6.67 wt% C
- Strong
- Hard
- Wear-Resistant
- Brittle
- Un-Weldable

α-Iron | Ferrite :

- 0.02 wt% C
- Weaker
- Soft
- Ductile
- Weldable

γ-Iron

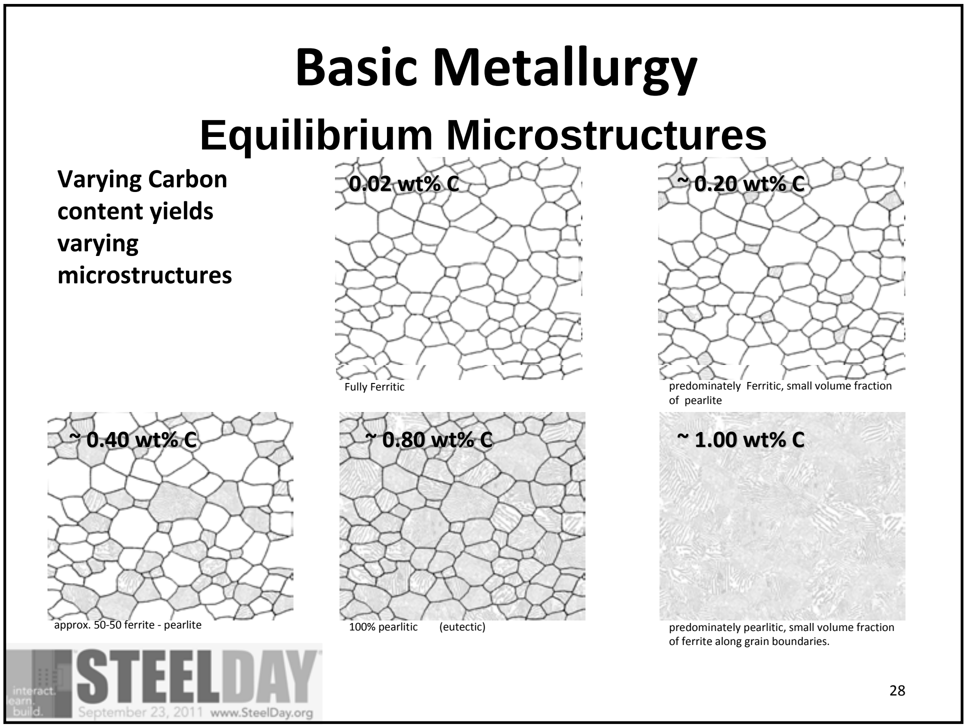
α-Iron

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

"technically: is a colony – not a "grain".

Typical Metallographic Appearance of Pearlite

Dark = Cementite
Light = Ferrite



Basic Metallurgy

Equilibrium Microstructures

Varying Carbon content yields varying microstructures

0.02 wt% C

Fully Ferritic

~ 0.20 wt% C

predominately Ferritic, small volume fraction of pearlite

~ 0.40 wt% C

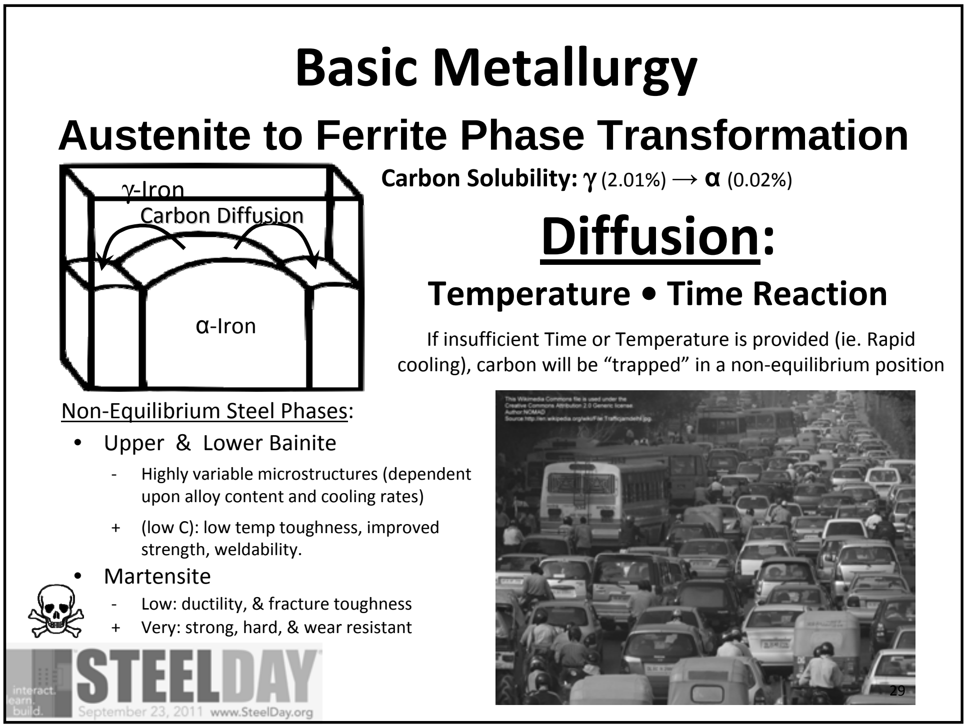
approx. 50-50 ferrite - pearlite

~ 0.80 wt% C

100% pearlitic (eutectic)

~ 1.00 wt% C

predominately pearlitic, small volume fraction of ferrite along grain boundaries.



Basic Metallurgy

Austenite to Ferrite Phase Transformation

Carbon Solubility: γ (2.01%) → α (0.02%)

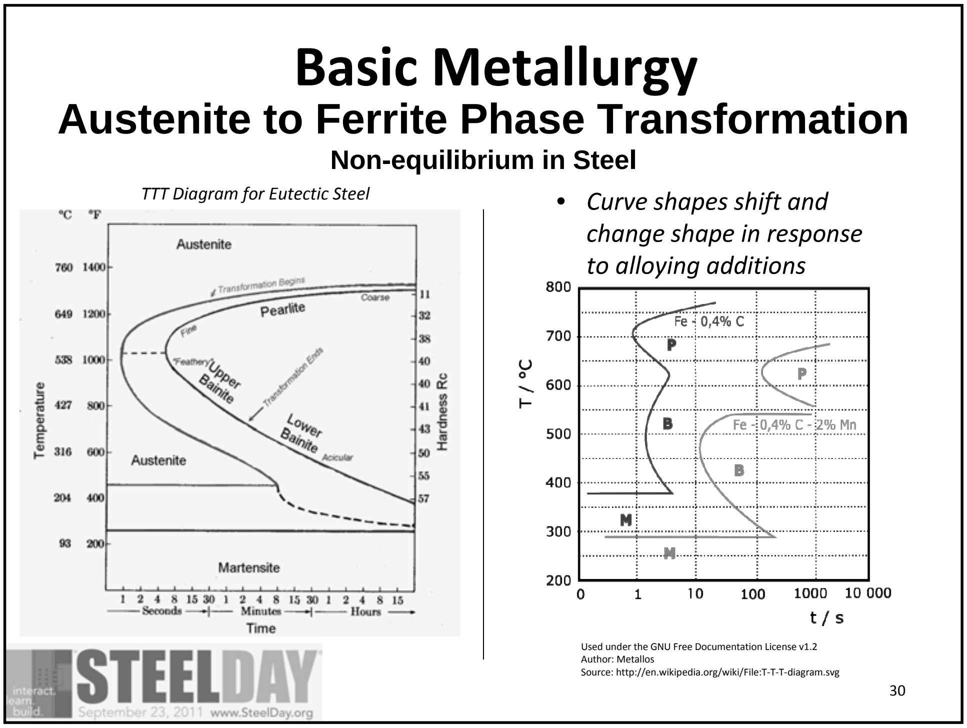
Diffusion:

Temperature • Time Reaction

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

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



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*

Used under the GNU Free Documentation License v1.2
Author: Metallos
Source: http://en.wikipedia.org/wiki/File:T-T-T-diagram.svg

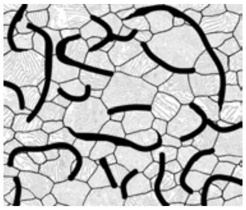
Basic Metallurgy

Austenite to Ferrite Phase Transformation

At equilibrium in Cast Iron

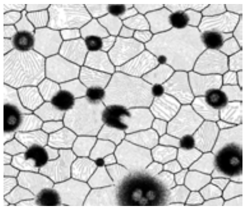
Gray Iron

- 3D network of graphite flakes in Pearlitic matrix



Ductile / Nodular Iron

- addition of elements (Mg) result in formation of graphite nodules instead of flakes.

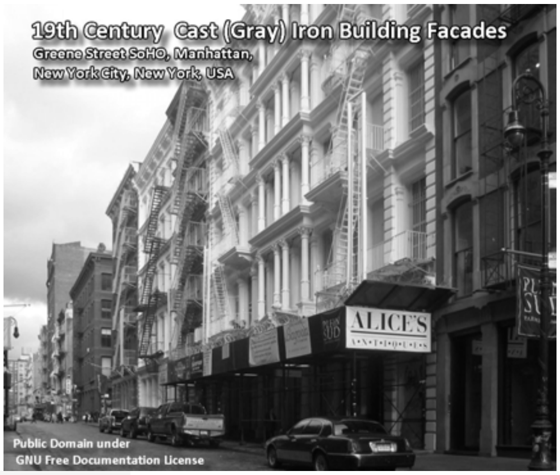


× Graphite = soft, low strength, acts like a "void".
× Flakes morphology = stress risers
× Low Strength
× **Low Ductility**
× **LOW NOTCH TOUGHNESS**
✓ Excellent machinability
✓ Good compressive strength
✓ Excellent "castability"

Cast Iron

Historic Structural Uses

Static / Compressive



19th Century Cast (Gray) Iron Building Facades
Greene Street SoHO, Manhattan, New York City, New York, USA

Public Domain under GNU Free Documentation License

Cast Iron

Historic Structural Uses

"Iron Bridge"

across the River Severn

Coalbrookdale, Shropshire, UK

<u>1st CAST IRON BRIDGEWORK</u>

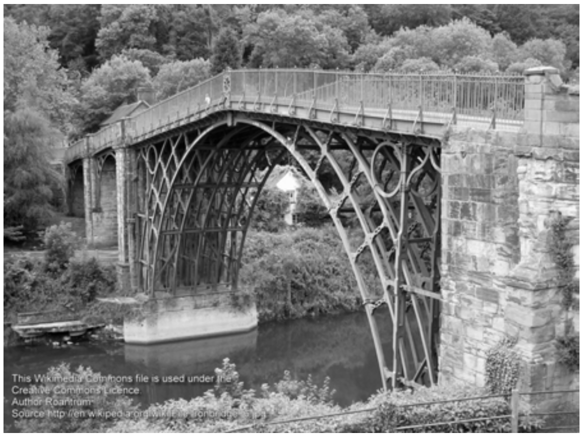
Opened: 1781
Closed to traffic: 1934, still standing
UNESCO "World Heritage Site"

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



This Wikimedia Commons file is used under the Creative Commons Licence.
Author Roantrum
Source http://en.wikipedia.org/wiki/[illegible]

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.

<u>Cast Iron Bridge Experiences: 1830 - 1891</u>

Dee Bridge, Chester, Cheshire, UK
Opened to Rail traffic: Sept 1846.
Failure: 24 May 1847. 5 fatalities. <u>Fracture of CI beam</u>

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

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

Ashtabula River Bridge, Ashtabula, OH
Failure: 29 Dec 1876. 92 fatalities, 64 injuries.
<u>Fatigue (?) of CI beam</u>.

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

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

11 June 1860 ● Wootton Bridge Collapse

This file is in the public domain due to expired copyright.

After <u>2nd</u> Norwood Junction Rail Bridge "incident", UK "Board of Trade" issues circular recommending gradual replacement of CI bridgework.

CAST IRONS <u>not</u> suitable for <u>Tension</u> nor <u>Cyclic Loading</u>

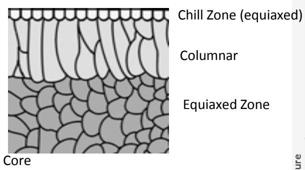
×Graphite = soft, low strength, acts like a "void".
×Flakes morphology = **<u>stress risers</u>**
×Low Strength, **<u>Low Ductility</u>**
×**<u>LOW NOTCH TOUGHNESS</u>**

Iron – Steel: What is the Difference ?

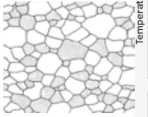
CAST Steel ≠ CAST Iron

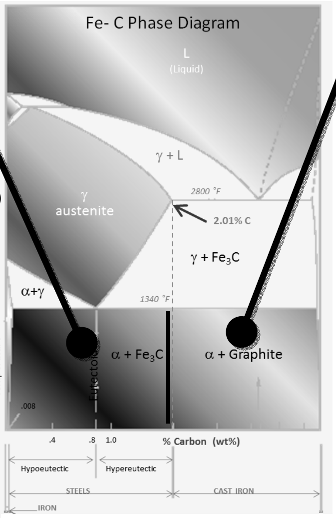
Cast Steels

- **Any "steel" composition**
- **Variable Cast Grain Structures**



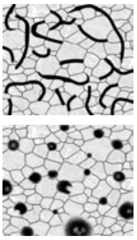
- **Ferrite**
- **Pearlite**





Cast Iron

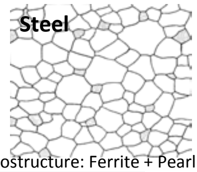
- **Pearlite + <u>Graphite</u>**



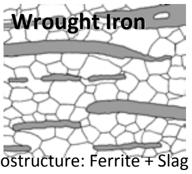
Iron – Steel: What is the Difference ?

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** ⇨ **Stacking** ⇨ **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** ↙ Oxide Inclusions
        Period literature claims slag content benefits <u>ductility and malleability</u> – more likely due to very low C / Mn.
      - ➢ **OBSOLETE –** (quality and manufacturing cost)



Microstructure: Ferrite + Pearlite



Microstructure: Ferrite + Slag

Iron – Steel: What is the Difference ?

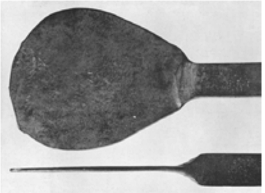

Image used under the Creative Commons Attribution Share Alike 3.0 Unported license
Author: Benh LIEU SONG, June 2009
Source: http://en.wikipedia.org/wiki/File:Tour_Eiffel_Wikimedia_Commons.jpg

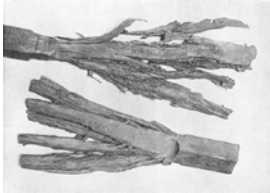
WROUGHT Iron

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 AUTOBIOGRAPH,Y WITH A CONCLUDING CHAPTER.
Universal Press, London 1905.


“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 ?
  - 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 \ ‘grād \ *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 }
A588 - Grades ‘A’,’B’,’C’,’K’ } definition 1, 2a

A36, A992 } Standard loosely definition 2b

Why Multiple Grades?

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.

Why Multiple Grades?

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).

"A572" = "Standard Specification" | "ASTM" = Specification Issuing/Controlling body

Grade: Specification detailing chemical and mechanical property requirements/restrictions

Why Multiple Grades?

Specification Issuing Bodies

		Focus
AASHTO	Association of American State Highway Transportation Officials	⇦ Bridge & Highway
ABS	American Bureau of Shipping	⇦ Ship Building
API	American Petroleum Institute	⇦ Petroleum Industry
ASTM	ASTM International	⇦ General/Specific
CSA	Canadian Standards Association	⇦ For use in Canada
SAE	Society of Automotive Engineers	⇦ 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: A709-50**T**x)
  - main load carrying member
  - Has redundancy or failure not expected to cause collapse
- Fracture Critical: (Grade designation: A709-50**F**x)
  - main load carrying tension member or tension component of bending member
  - Failure expected to lead to collapse

Why Multiple Grades?

Specific Product Application

Example : ASTM **A709-50** vs ASTM **A709-50Tx** vs ASTM **A709-50Fx**

A709 CVN Testing Requirements *(≤ 2" Shape)*		**Minimum Average Energy (ft-lbf)**		
Fracture "Condition"		**Zone 1**	**Zone 2**	**Zone 3**
Non- Critical	**(T)**	**15 @ 70°F**	**15 @ 40°F**	**15 @ 10°F**
Critical	**(F)**	**25 @ 70°F**	**25 @ 40°F**	**25 @ 10°F**
Service Temperature (°F)		0°F	>0°F to -30°F	>-30°F to -60°F

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

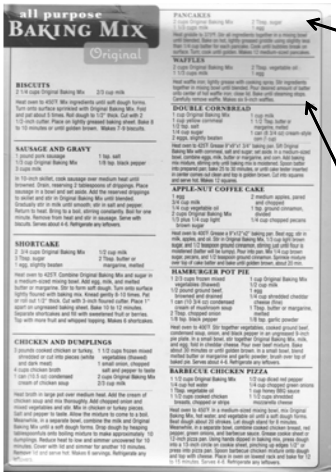
Example : ASTM **A572-50** vs ASTM **A992 (Structural Shapes)**

- 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



all purpose BAKING MIX Original

BISCUITS
2 1/4 cups Original Baking Mix 2/3 cup milk

SAUSAGE AND GRAVY
1 pound pork sausage 1 tsp. salt
1/3 cup Original Baking Mix 1/8 tsp. black pepper
3 cups milk

SHORTCAKE
2 3/4 cups Original Baking Mix 1/2 cup milk
3 Tbsp. sugar 2 Tbsp. butter or margarine, melted
1 egg, slightly beaten

CHICKEN AND DUMPLINGS

PANCAKES
2 cups Original Baking Mix 2 Tbsp. sugar
1 1/3 cups milk 1 egg

WAFFLES
2 cups Original Baking Mix 2 Tbsp. vegetable oil
1 1/3 cups milk 1 egg

DOUBLE CORNBREAD

APPLE-NUT COFFEE CAKE

HAMBURGER POT PIE

BARBECUE CHICKEN PIZZA

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…*

Similar processing
Different product

Same "chemistry"

- ➢ Same chemistry
- ➢ Deviation in Processing – Different Product

❑ Might or Might Not be in same specification.

Why Multiple Grades?

Multi-Certification

What is the W16x36's MTR Grade ?

"..." denotes no requirement(s)

			*ASTM Specification / Grade								W16x36	
			A36^{-08}		A572-50 Type 2^{-07}		A709-50 Type 2^{-10}		A992^{-06a}		MTR analysis	
		Units	min	max	min	max	min	max	min	max		
Chemical Requirements	C	wt%	...	.26	...	.23	...	.23	...	.23	**.09**	
	Mn	wt%	...	...	...	1.35	...	1.35	.50	1.50	**.89**	
	S	wt%	...	.05	...	.05	...	.05	...	.045	**.021**	
	P	wt%	...	.04	...	.04	...	.04	...	.035	**.013**	
	Si	wt%	...	.40	...	.40	...	.40	.10	.40	**.22**	
	Cu	wt%	...	...	...	...	...	...	...	.60	**.24**	
	Ni	wt%	...	...	...	...	...	...	...	.45	**.09**	
	Cr	wt%	...	...	...	...	...	...	...	.35	**.10**	
	Mo	wt%	...	...	...	...	...	...	...	.15	**.028**	
	V	wt%	...	...	.01	.15	.01	.15	...	.15	**.019**	
	Nb	wt%	...	...	...	...	...	...	...	.05	**.001**	
	V+Nb	wt%	...	...	...	...	...	...	...	.15	**.020**	
	Sn	wt%	...	...	...	...	...	...	"report"		**.01**	
	CE		...	...	...	...	...	...	...	.45	**.29**	
Mechanical Reqmnt's	f_y	ksi	36	...	50	...	50	...	50	65	**60**	**61**
	f_u	ksi	58	80	65	...	65	...	65	...	**73**	**75**
	f_y/f_u		...	...	...	...	...	...	...	.85	**.82**	**.81**
	elong.	%	20	...	18	...	18	...	18	...	**28**	**29**

* Requirements assuming: (1) Shape, (2) Flange Tested, (3) $t_f \leq 2$", (4) no "footnoted" alternatives used.

Why Multiple Grades?

Multi-Certification

First Name: Doug

Last Name: Rees-Evans

Nicknames: "Reesy" (grade school)

You can call me:

- Doug
- *... only if you're my mother.* → Douglas
- Mr. Rees-Evans
- *... I won't answer !* → 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?

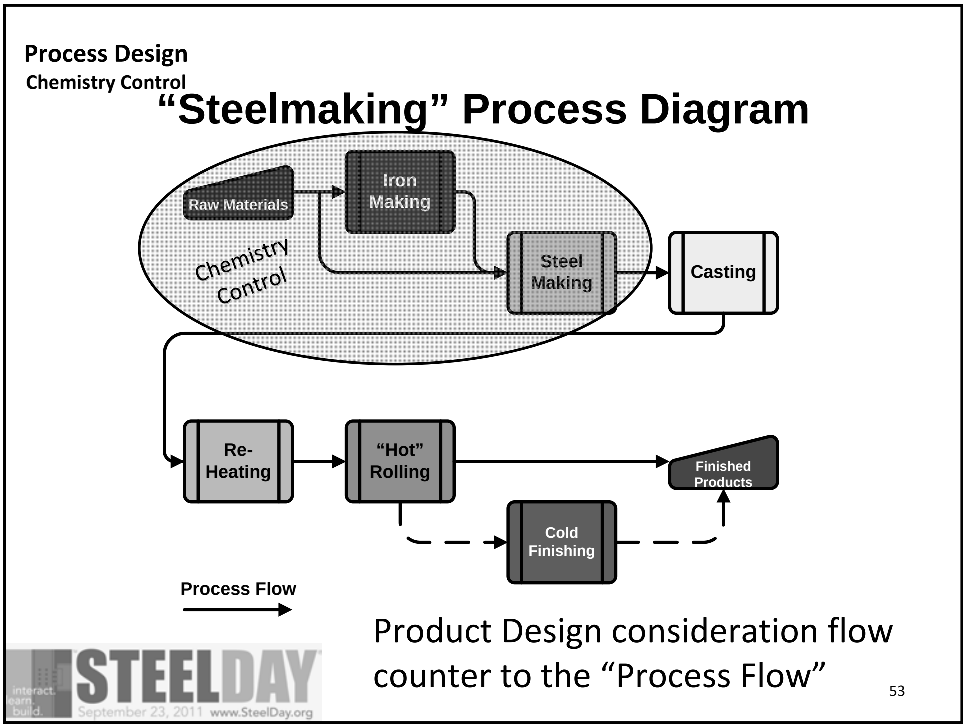
A. The difference is due to…..

- **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

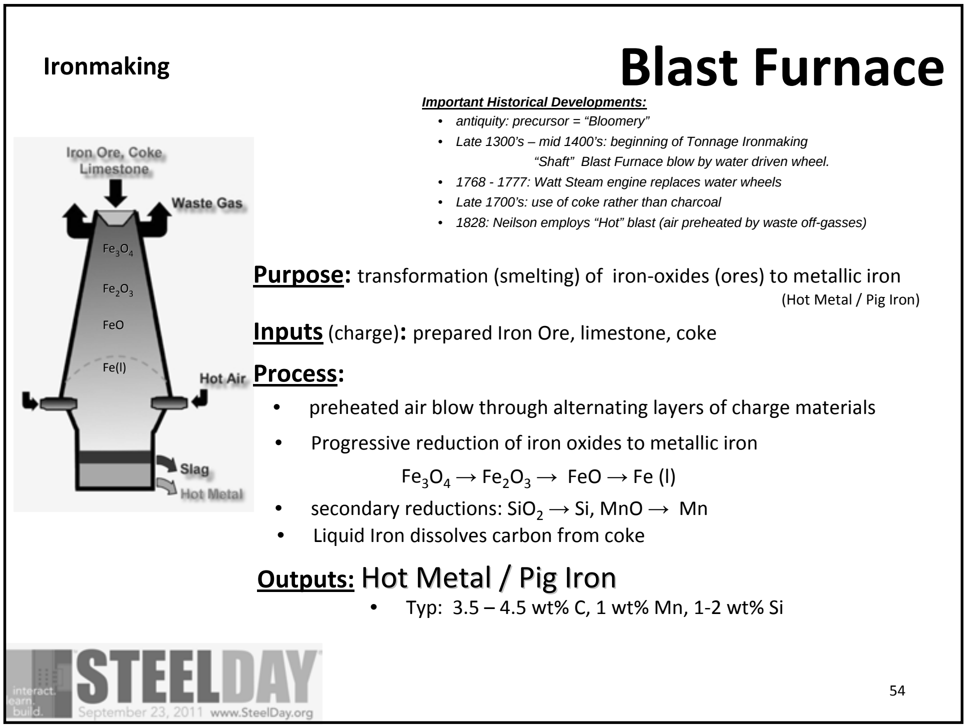
- ✓ Iron – Steel: What is the Difference ?
- ✓ Why are there multiple Grades of Steel ? Isn't steel, steel ?
- ➢ How can a mill control chemistry ? Isn't it dependent upon what scrap is used ?
  - o How does a mill control the properties of a steel product ?
- If I retest a product, will I get the same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



Process Design
Chemistry Control

“Steelmaking” Process Diagram

Product Design consideration flow counter to the “Process Flow”



Ironmaking

Blast Furnace

Important Historical Developments:
- *antiquity: precursor = “Bloomery”*
- *Late 1300’s – mid 1400’s: beginning of Tonnage Ironmaking*
  “Shaft” Blast Furnace blow by water driven wheel.
- *1768 - 1777: Watt Steam engine replaces water wheels*
- *Late 1700’s: use of coke rather than charcoal*
- *1828: Neilson employs “Hot” blast (air preheated by waste off-gasses)*

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

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

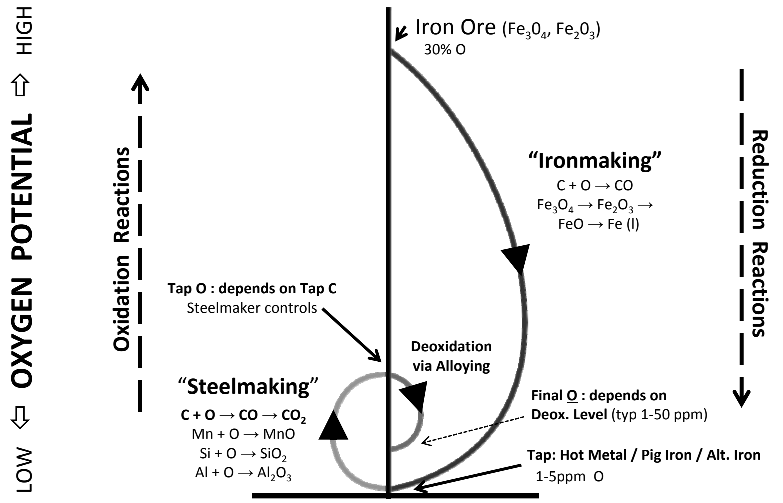
Process:
- preheated air blow through alternating layers of charge materials
- Progressive reduction of iron oxides to metallic iron
  $Fe_3O_4 \rightarrow Fe_2O_3 \rightarrow FeO \rightarrow Fe\ (l)$
- secondary reductions: $SiO_2 \rightarrow Si$, $MnO \rightarrow Mn$
- Liquid Iron dissolves carbon from coke

Outputs: Hot Metal / Pig Iron
- Typ: 3.5 – 4.5 wt% C, 1 wt% Mn, 1-2 wt% Si

Process Design

Chemistry Control

Oxygen Map of Iron and Steel Making



LOW ⇩ **OXYGEN POTENTIAL** ⇧ HIGH

Oxidation Reactions

Reduction Reactions

Iron Ore (Fe_30_4, Fe_20_3)
30% O

"Ironmaking"
$C + O \rightarrow CO$
$Fe_3O_4 \rightarrow Fe_2O_3 \rightarrow FeO \rightarrow Fe\ (l)$

Tap O : depends on Tap C
Steelmaker controls

Deoxidation via Alloying

"Steelmaking"
$C + O \rightarrow CO \rightarrow CO_2$
$Mn + O \rightarrow MnO$
$Si + O \rightarrow SiO_2$
$Al + O \rightarrow Al_2O_3$

Final <u>O</u> : depends on Deox. Level (typ 1-50 ppm)

Tap: Hot Metal / Pig Iron / Alt. Iron
1-5ppm O

Ironmaking

"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

<u>Alternative to Blast Furnace</u>

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

<u>Example Processes:</u>

- **Pre 1980's : MIDREX / HYL Process / FINMET**
- **1990's : Iron Carbide** (Nucor) **/ Iron Dynamics*** (SDI)

*DRI melted in submerged Arc Furnace

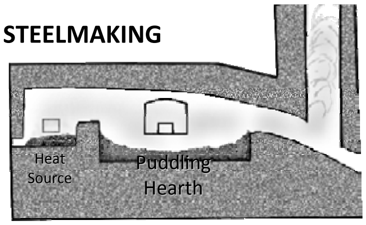
- **2000's : ITmk3 / Mesabi Iron Nuggets**

STEELMAKING

Puddling

*<u>**Important Historical Developments:**</u>*

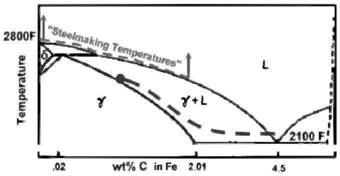
- *1613: Reverberatory Furnace Invented*
- *1760: Puddling Process Invented*
- *1890's: Wrought Iron for structural applications largely replaced by steel*
- *1925: Aston Process: Bessemer "iron" replaces pig iron + reverberatory furnaces route. – **Puddling OBSOLETE**.*
- *Last commercial production of "true" wrought iron : USA 1969; UK 1973*



Puddling Furnace

Heat Size: 750 – 1500 # (typical)
Tap-Tap: 4 – 6 hr

Partial, High-Temp Fe-C Phase Diagram



Red line (right to left) approximates composition and temperature changes during Puddling

<u>Inputs</u> (charge)**:** Pig Iron, Heat (fuel – coke / coal)

<u>Process</u> :

- Pig iron melted in the hearth of a reverberatory furnace
- Liquid stirred with a pole to expose to air.
- Dissolved C oxidizes (surface liquid) reducing carbon content. Liquid composition moves into γ+L phase ("mushy" puddle).
  - Dissolved Si, Mn oxidize (slag)

} raises temp. (not hot enough to reach "steelmaking" temps)

- Comes "of nature" when C & temp reaches γ(solid) phase.
- "**<u>pasty ball</u>**" removed from furnace and hammer/rolled to "squeeze-out" slag
- Rolled/hammered pieces are sheared, stacked, reheated and rerolled (wrought) into <u>merchant bar</u>

<u>Outputs</u> : Wrought Iron

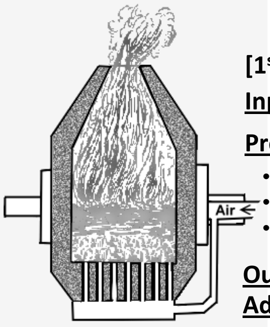
- Typ: .10 – .20 wt% C (max .05 - .25)
- Extremely variability in C content between "batches"
- Negligible Mn, Si

STEELMAKING

*<u>**Important Historical Developments:**</u>*

- *1856: Bessemer demonstrates his "converter"*
- *1865: 1st US Production of "Bessemer" Steel*
- *1879: Thomas Process / Basic Bessemer Steel*
- *1949: Last "New" Bessemer Converter installation in US*
- *1966: Last commercial production Bessemer Steel in US*

Bessemer



Heat Size: 15 -20 ton (typical)
Tap-Tap: 20 – 30 min

[1st "tonnage" Steelmaking]

<u>Inputs</u> : Hot Metal, Air

<u>Process</u> :

- 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 ⇨ C ⇨ Fe = ⇧ TEMPERATURE

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

<u>Advantages</u> : (over Puddling)

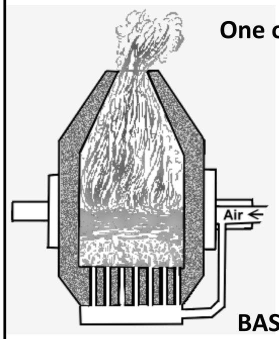
- Speed: 20 tons in 30 mins vs ¾ tons in 4-6 hrs
- Autogenous : – no external heat / energy required
- Cost: price of finished steel in <u>1865</u> (converted to 2010 USD).
  Puddle Iron: **$5,000/ton** | Bessemer Steel: $800/ton

<u>Difficulties</u> :

- Cannot remove Sulfur nor Phosphorous (no slag)
- Process speed too rapid for real-time chemical analysis
- Cannot use scrap

STEELMAKING

“ACID” VS “BASIC”



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 (SiO_2) based.

BASIC Slag / Refractory = Lime (CaO_2) / Dolomitic (CaO_2, MgO) based.

ACID “practice” uses ACID refractories ● BASIC “practice” uses BASIC refractories

* In Europe, due to high P-bearing ores, the “Basic” Bessemer Process was wide 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 predominate.

Process Design
STEELMAKING

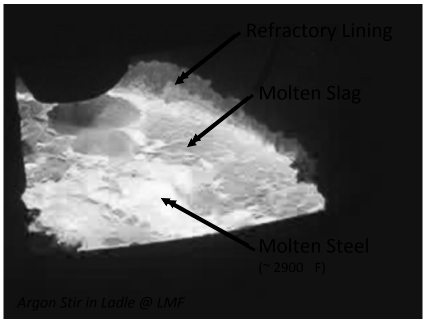
“Refractories” & “Slags”

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, Al_2O_3, SiO_2, 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 slag modifiers.
- Used Slag: crushed, classified – used as concrete aggregate, road-base, RR ballast, etc.

STEELMAKING

Open Hearth

(Seismen's Process)

Acid / Basic

Important Historical Developments:
- *1860: Seismen's (OH) Process invented*
- *1870: 1st US production of Open Hearth Steel (Boston, MA)*
- *1888: 1st US "Basic" Open Hearth furnace (US Steel – Homestead Works)*
- *1967: Last commercial OH steel production - USA*
- *2001: Last commercial world-wide OH steel production – (China)*

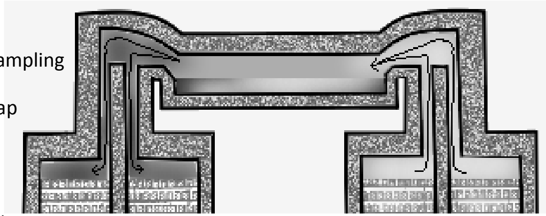
Inputs : Hot Metal, Fuel, Air, Slag Formers, Scrap &/or Pig Iron

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 ⇨ 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).



Heat Size: 50 -300 ton
(typical – 150 – 300 ton)

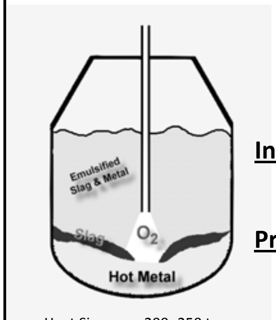
Tap-Tap: 4 – 6 hr

STEELDAY interact. learn. build. September 23, 2011 www.SteelDay.org

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)*



Heat Size: 200 -250 ton
(typical)

Tap-Tap: 30min – 1 hr

Several different configurations

Top-Blown, Bottom-Blown, combination

PRIMARY INPUT

Inputs :
- "Iron Units" - Scrap, Pig Iron, Alt. Iron, Hot Metal
- Slag Formers and Fluxes
- Energy$_{\text{(chemical)}}$ – Supersonic O_2

Process :

Charge Solids ⇨ Charge Hot Metal ⇨ Blow ⇨ Tap

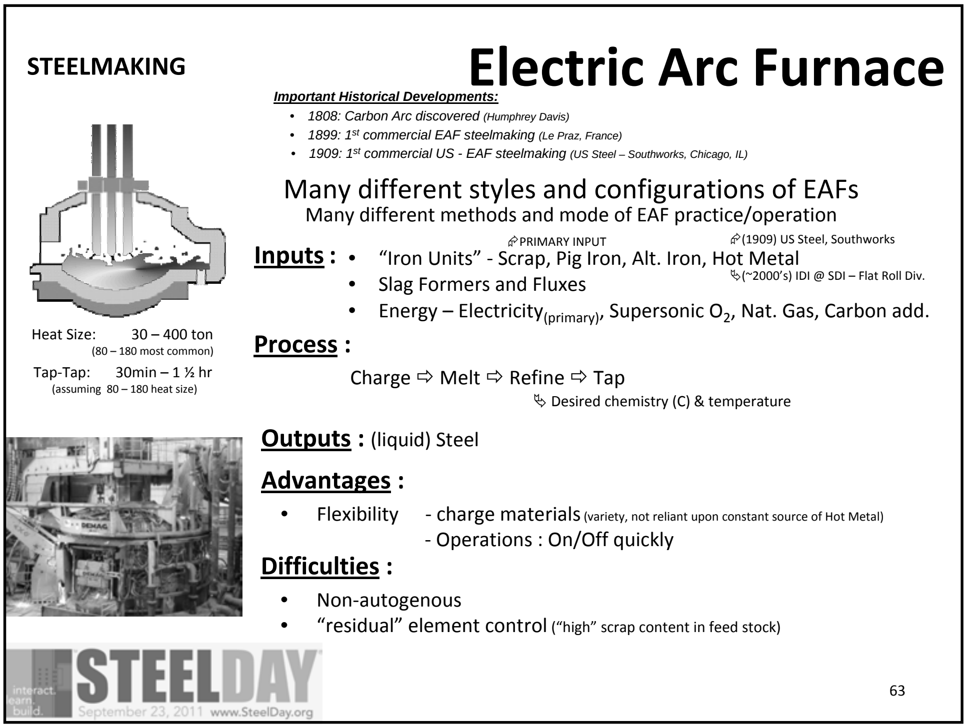
Preferential oxidation of dissolved elements: Si, Mn ⇨ C : Heat

Outputs : (liquid) Steel

Advantages :
- Autogenous (REQUIRES NO EXTERNAL ENERGY SOURCE)
- Dilution of "residual" elements

Difficulties :
- Requires continual Hot Metal supply

STEELDAY interact. learn. build. September 23, 2011 www.SteelDay.org



STEELMAKING

Electric Arc Furnace

Important Historical Developments:

- *1808: Carbon Arc discovered (Humphrey Davis)*
- *1899: 1st commercial EAF steelmaking (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

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

Inputs :
- "Iron Units" - Scrap, Pig Iron, Alt. Iron, Hot Metal
  - ⇗ PRIMARY INPUT (Scrap)
  - ⇗ (1909) US Steel, Southworks
  - ⇘ (~2000's) IDI @ SDI – Flat Roll Div.
- Slag Formers and Fluxes
- Energy – Electricity$_{(primary)}$, Supersonic O_2, Nat. Gas, Carbon add.

Process :

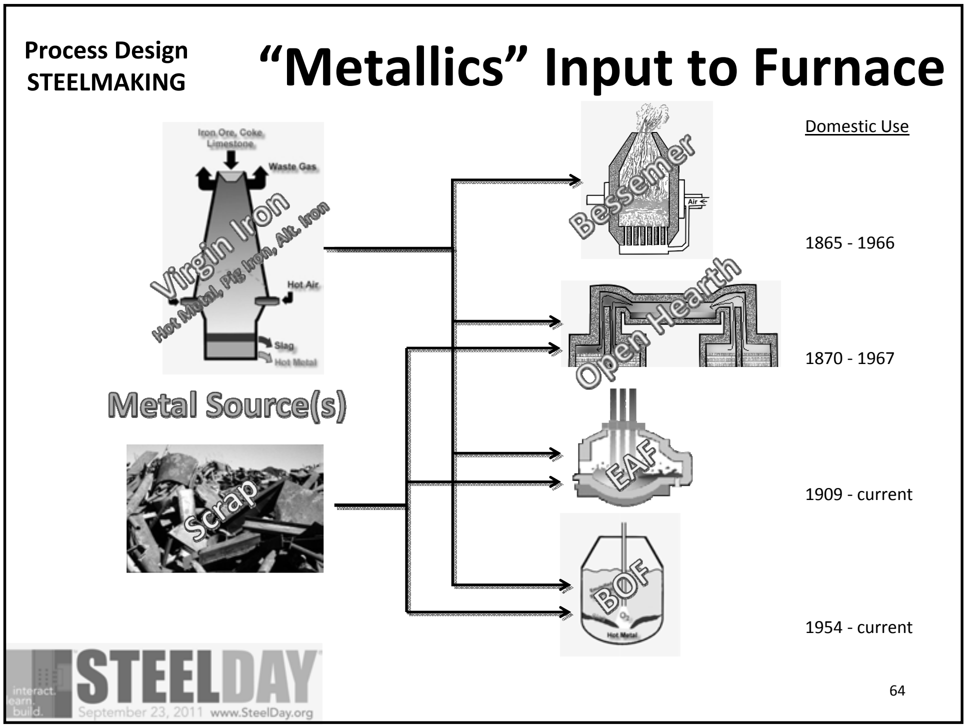
Charge ⇨ Melt ⇨ Refine ⇨ Tap
⇘ Desired chemistry (C) & temperature

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)

63



Process Design
STEELMAKING

"Metallics" Input to Furnace

Domestic Use

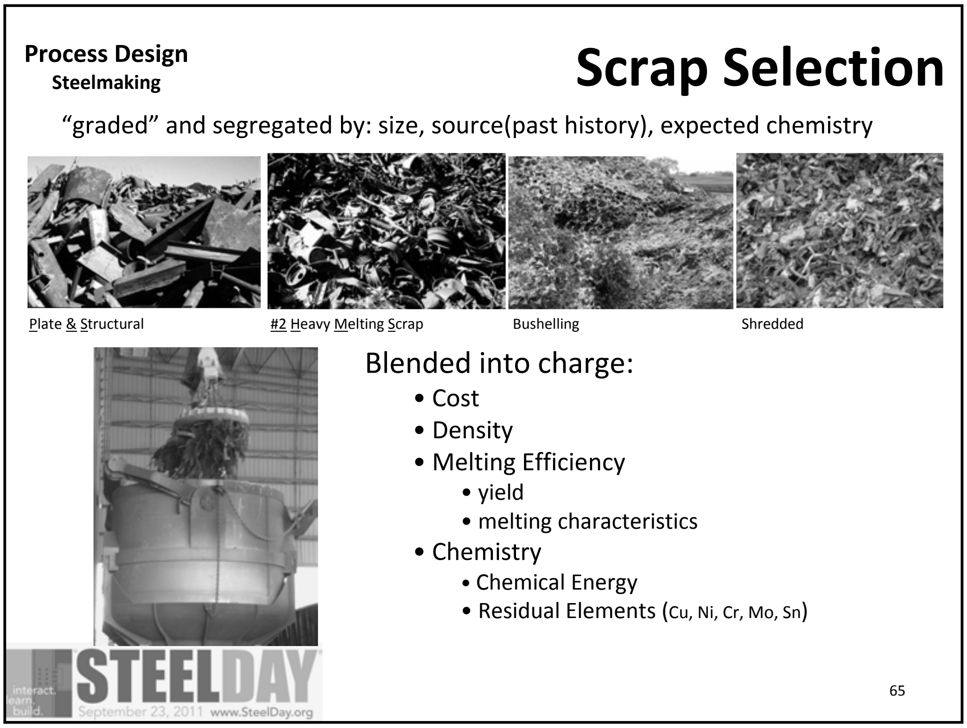
1865 - 1966

1870 - 1967

1909 - current

1954 - current

64



Process Design
Steelmaking

Scrap Selection

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

Plate & Structural

#2 Heavy Melting Scrap

Bushelling

Shredded

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…

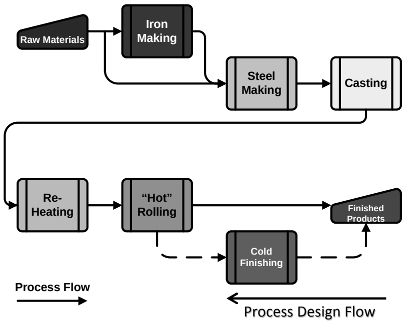
MP = *f* (chemistry , microstructure)

Re-defined question:

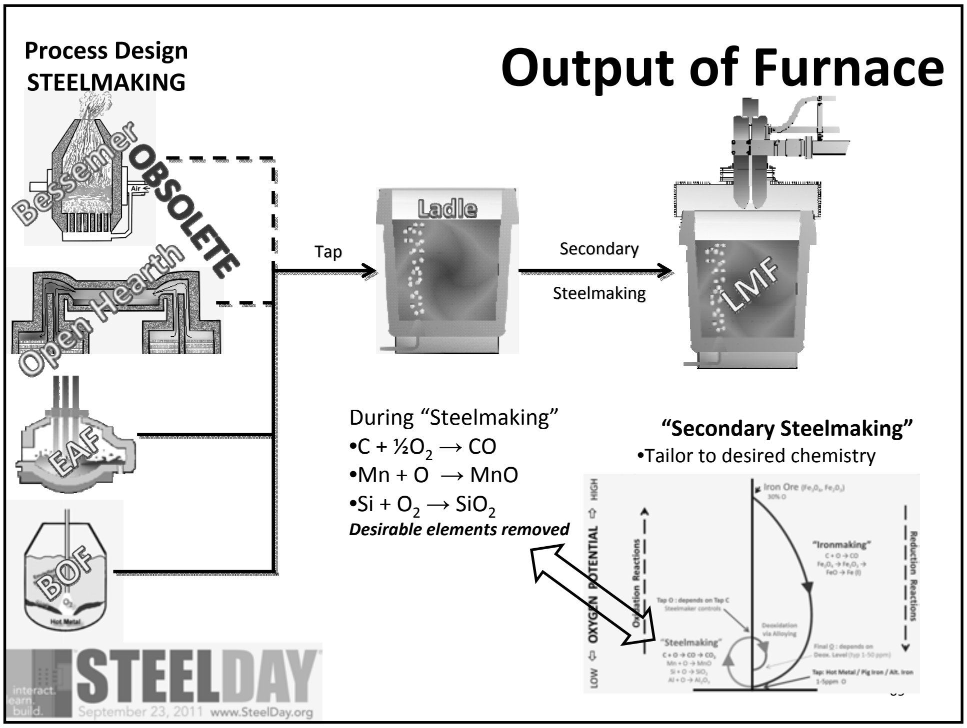
How does a mill control the properties of a steel product ?

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
   - ✓ COT !!



1 + 2 → which technology solution to employ



Process Design
STEELMAKING

Output of Furnace

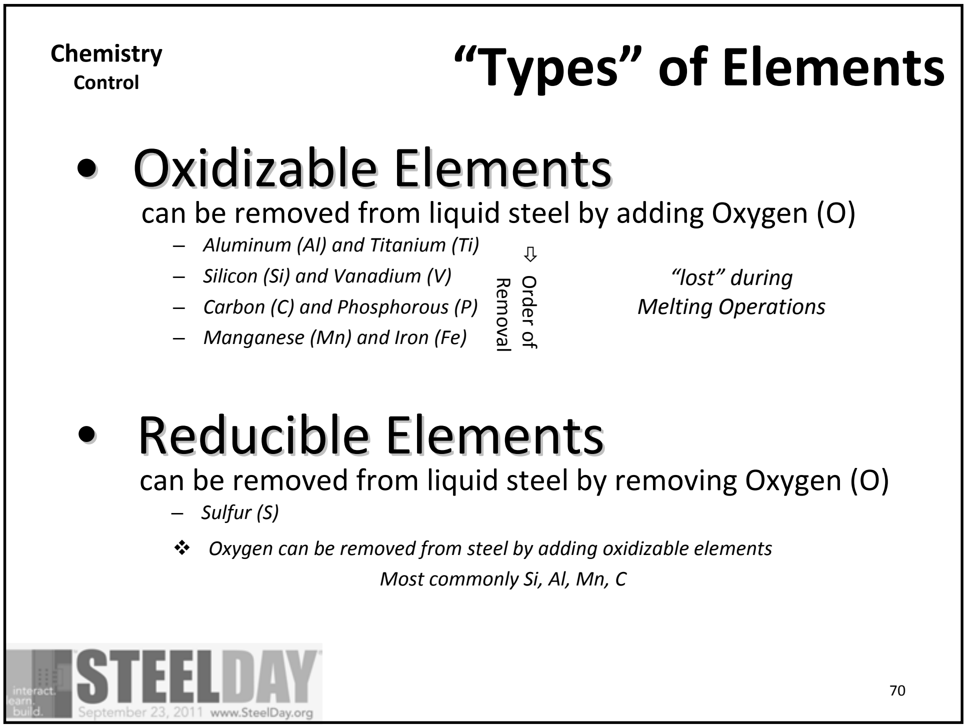
During “Steelmaking”

- $C + ½O_2 \rightarrow CO$
- $Mn + O \rightarrow MnO$
- $Si + O_2 \rightarrow SiO_2$

Desirable elements removed

“Secondary Steelmaking”

- Tailor to desired chemistry



Chemistry
Control

“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

Chemistry
Control

“Types” of Elements

- Other Elements

can not 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.

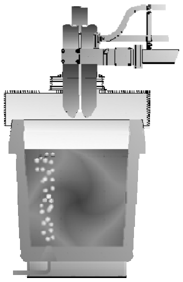
Controlled through the careful selection of type and quantities of raw materials.

Element wt% = as melted

- When purposefully added, known as: Alloying Elements
- When arriving from raw material stream (eg. Scrap, Ore), Known as : Residual Elements

Process Design
STEELMAKING

Secondary Steelmaking

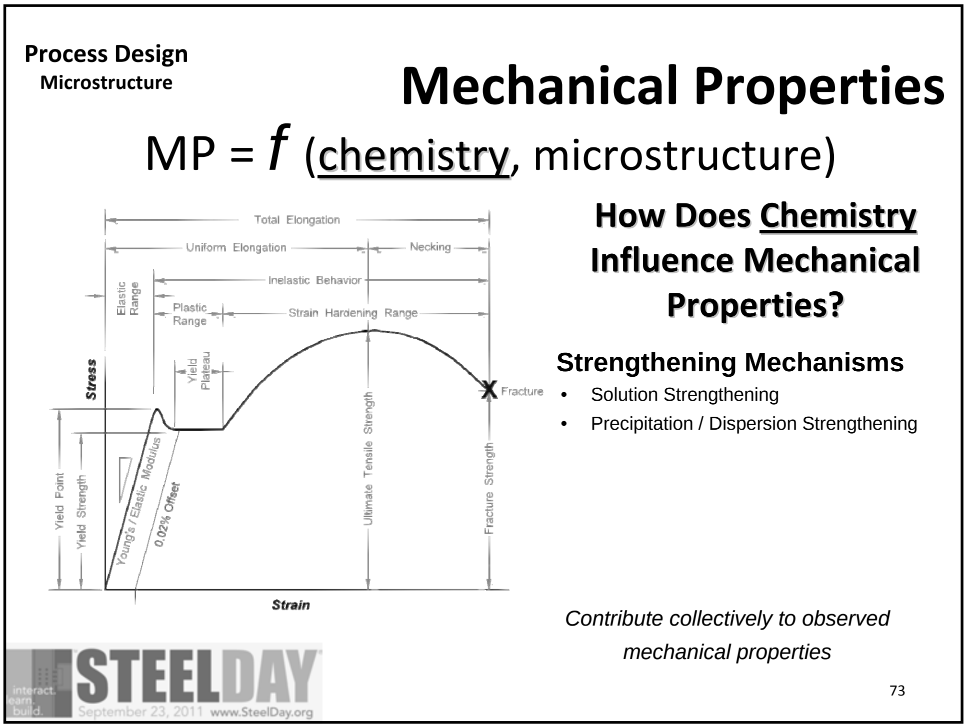


Ladle Metallurgy Furnace

- 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)



Process Design
Microstructure

Mechanical Properties

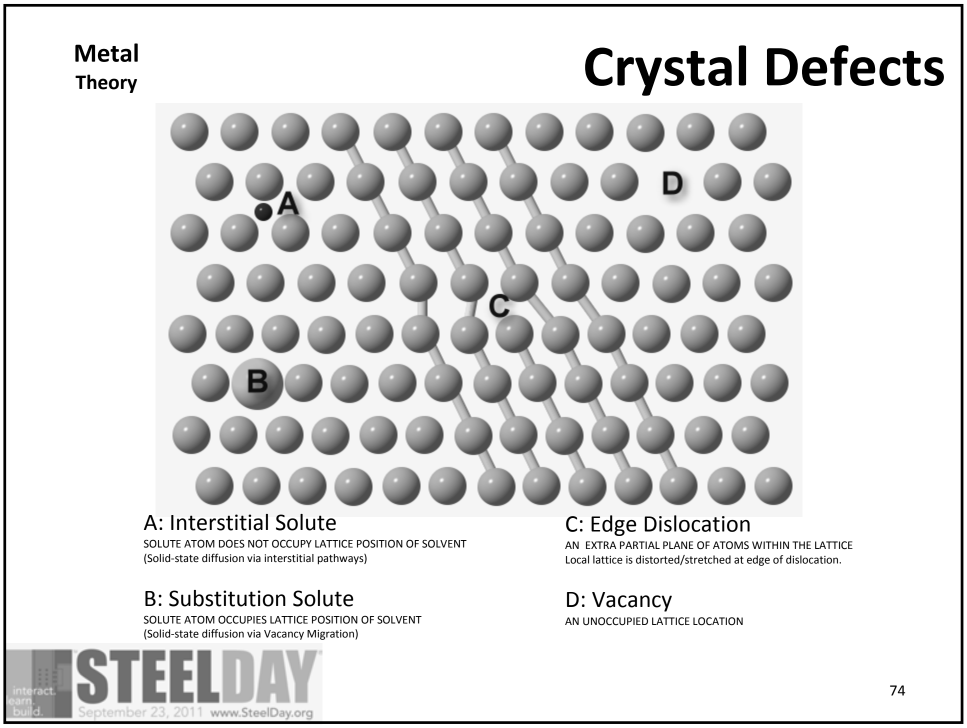
MP = *f* (chemistry, microstructure)

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.

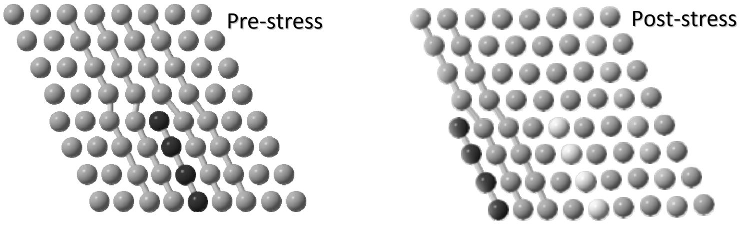
D: Vacancy
AN UNOCCUPIED LATTICE LOCATION

Metal
Theory

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.



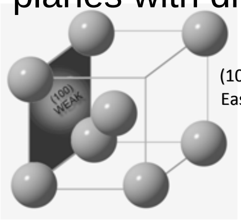
Plastic Deformation = Dislocation Slip

- 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 require to slip dislocations is on the order of x10^2 ***less*** than is required to cause slip of entire (full) plane of atoms. Permanent Shape Change.

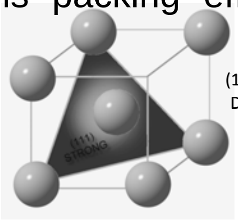
Metal
Theory

Crystal Anisotropy

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



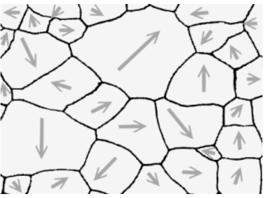
(100) Plane in BCC Iron
Easy slip ⇨ "Weak"



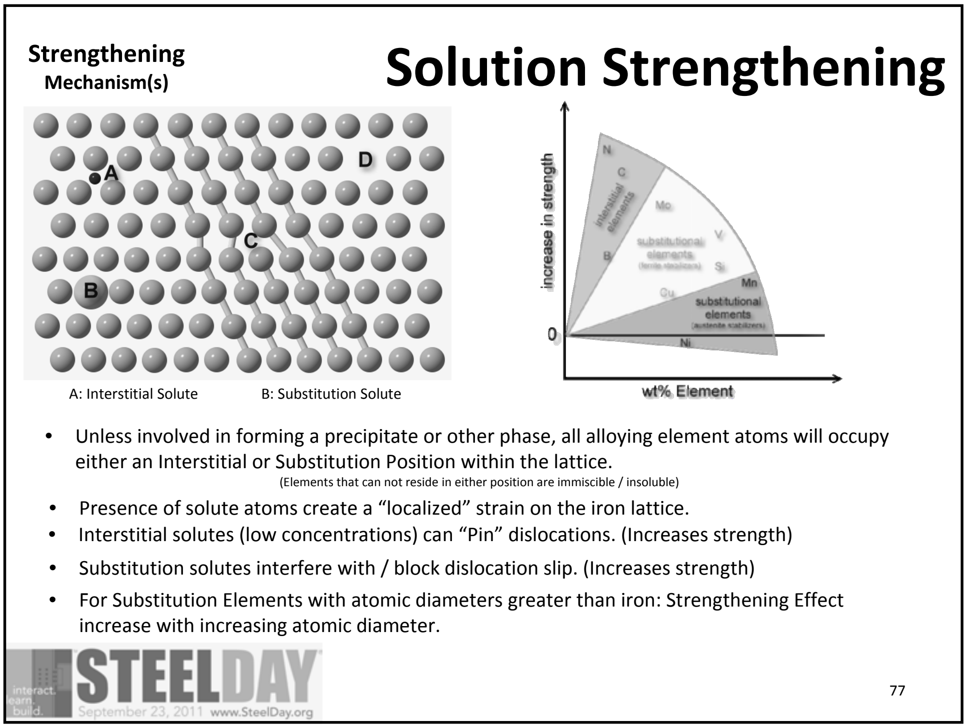
(111) Plane in BCC Iron
Difficult slip ⇨ "Strong"

different planes offer different resistances to dislocation motion

@ Grain Level :
Steel = ANISOTROPIC
<< Different strengths in different directions >>



@ Macro Level:
randomly oriented grains exhibit "average" behavior

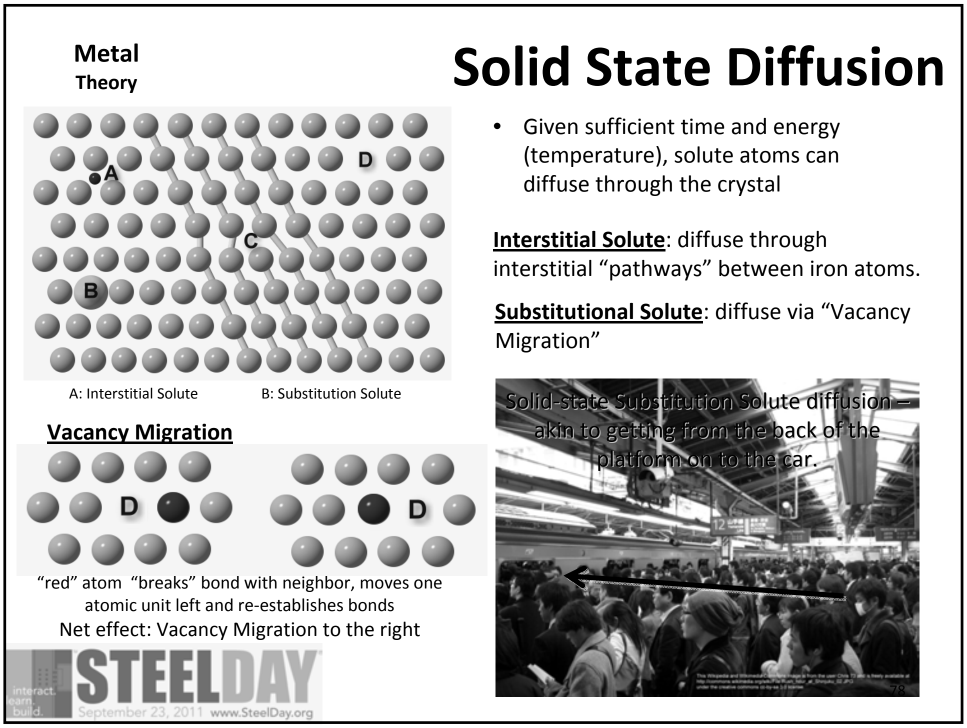


Strengthening
Mechanism(s)

Solution Strengthening

A: Interstitial Solute B: Substitution Solute

- Unless involved in forming a precipitate or other phase, all alloying element atoms will occupy either an Interstitial or Substitution Position within the lattice.
  (Elements that can not reside in either position are immiscible / insoluble)
- 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.



Metal
Theory

Solid State Diffusion

A: Interstitial Solute B: Substitution Solute

Vacancy Migration

"red" atom "breaks" bond with neighbor, moves one atomic unit left and re-establishes bonds

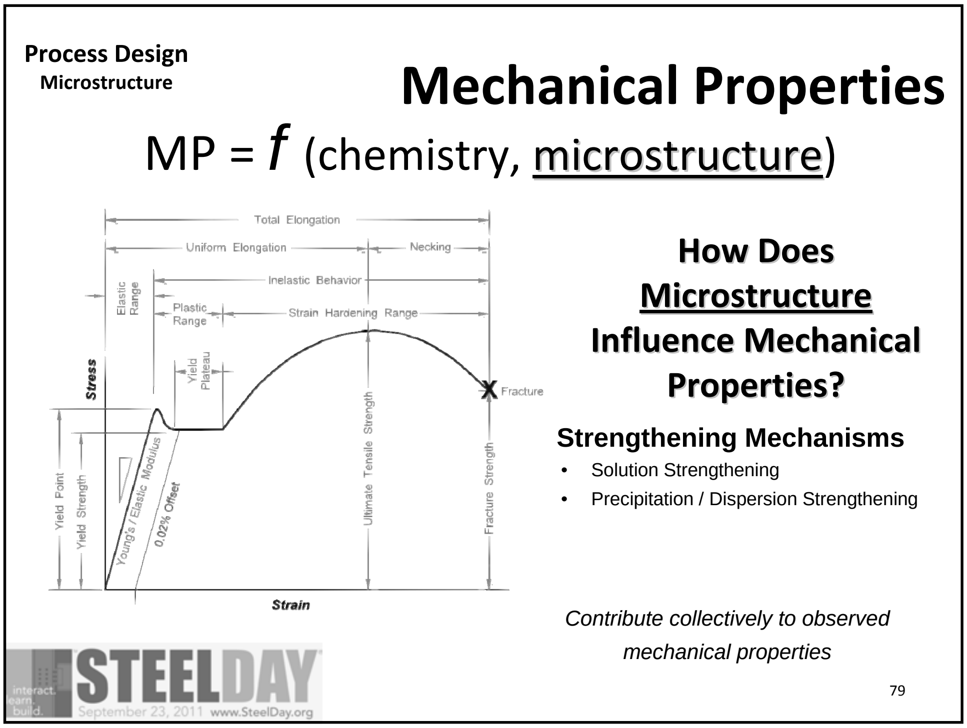
Net effect: Vacancy Migration to the right

- 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"

Solid-state Substitution Solute diffusion – akin to getting from the back of the platform on to the car.



Process Design
Microstructure

Mechanical Properties

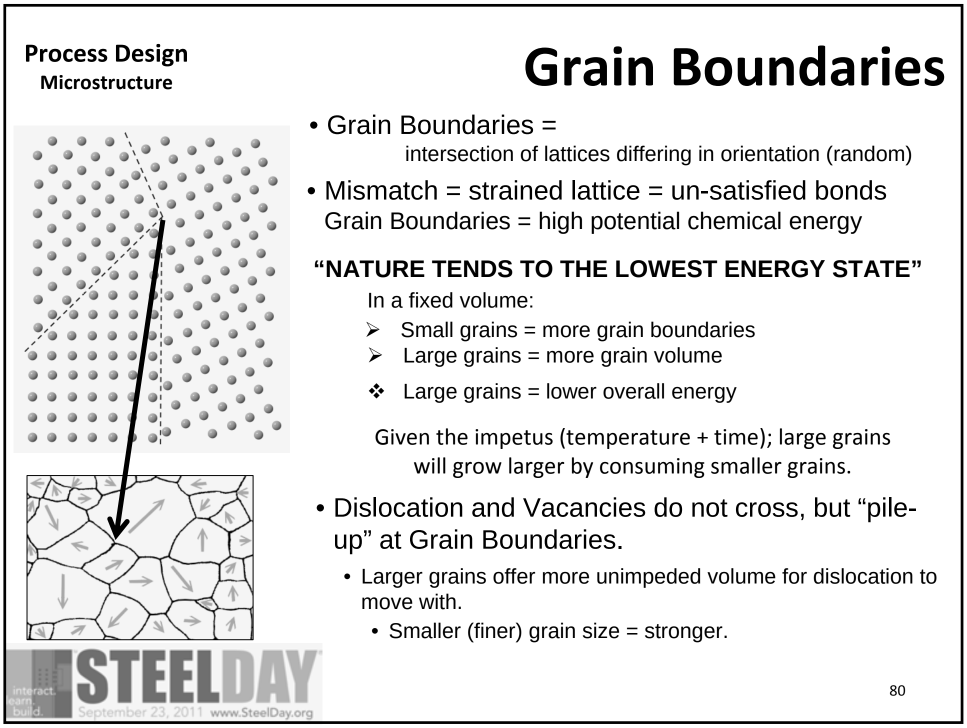
MP = *f* (chemistry, <u>microstructure</u>)

How Does <u>Microstructure</u> Influence Mechanical Properties?

Strengthening Mechanisms

- Solution Strengthening
- Precipitation / Dispersion Strengthening

Contribute collectively to observed mechanical properties



Process Design
Microstructure

Grain Boundaries

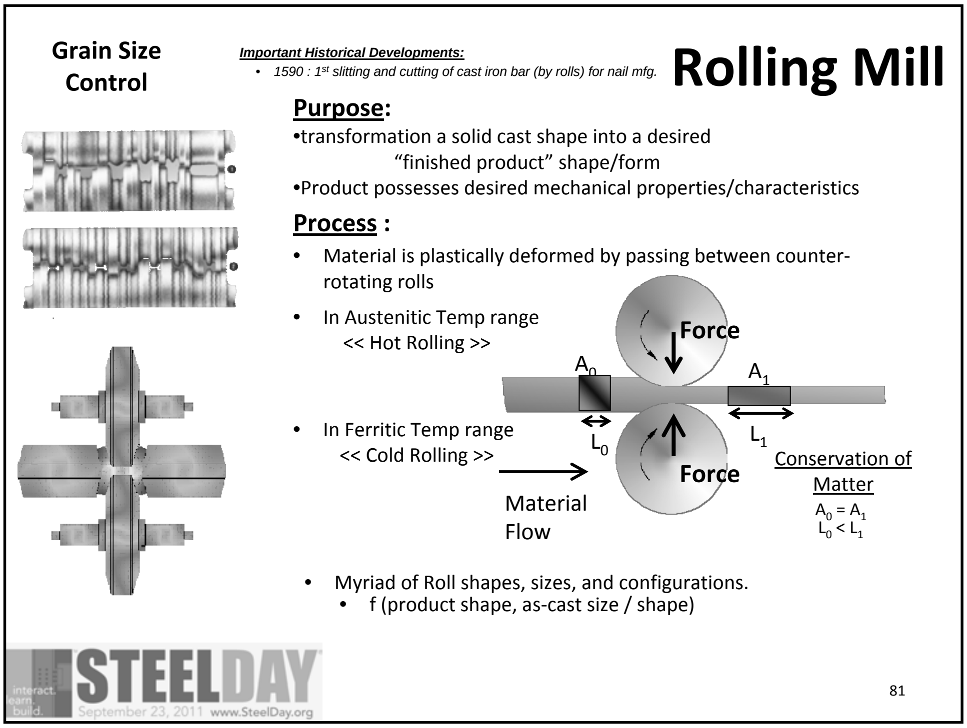
- Grain Boundaries =
  intersection of lattices differing in orientation (random)
- Mismatch = strained lattice = un-satisfied bonds
  Grain Boundaries = high potential chemical energy

"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.



Grain Size Control

Important Historical Developments:

- *1590 : 1st slitting and cutting of cast iron bar (by rolls) for nail mfg.*

Rolling Mill

Purpose:

- transformation a solid cast shape into a desired "finished product" shape/form
- Product possesses desired mechanical properties/characteristics

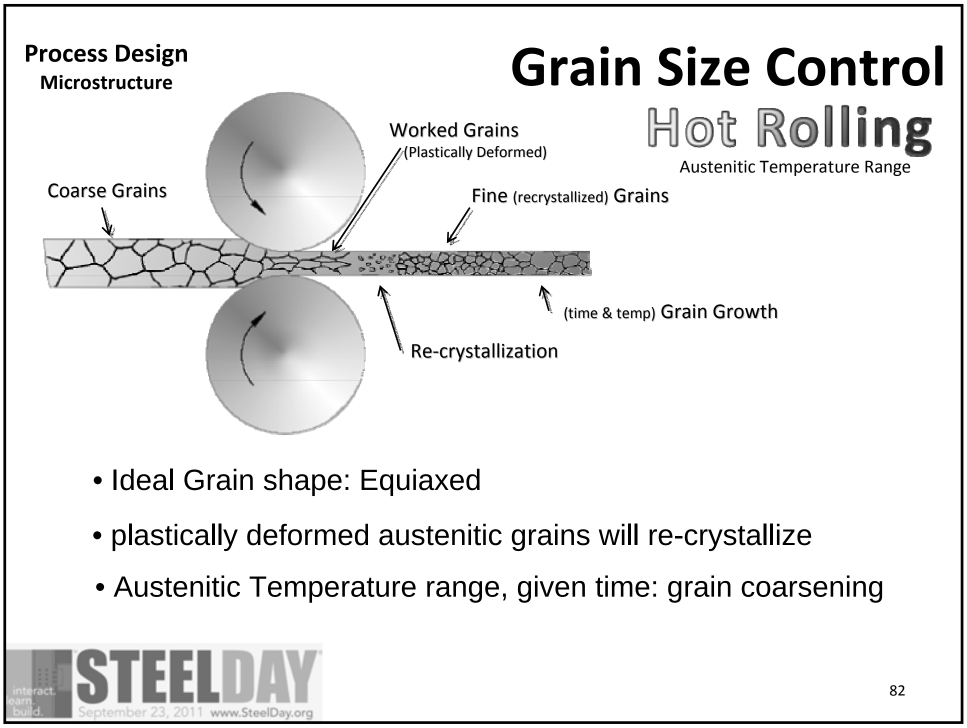
Process :

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

Conservation of Matter

$A_0 = A_1$
$L_0 < L_1$

- Myriad of Roll shapes, sizes, and configurations.
  - f (product shape, as-cast size / shape)



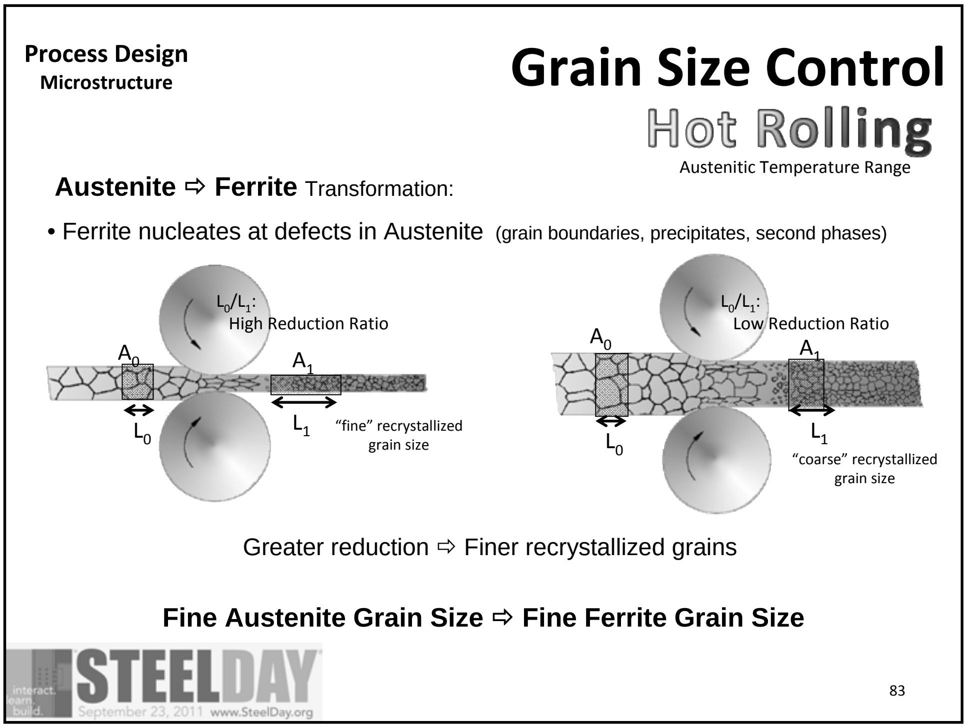
Process Design
Microstructure

Grain Size Control

Hot Rolling

Austenitic Temperature Range

- Ideal Grain shape: Equiaxed
- plastically deformed austenitic grains will re-crystallize
- Austenitic Temperature range, given time: grain coarsening



Process Design
Microstructure

Grain Size Control

Hot Rolling

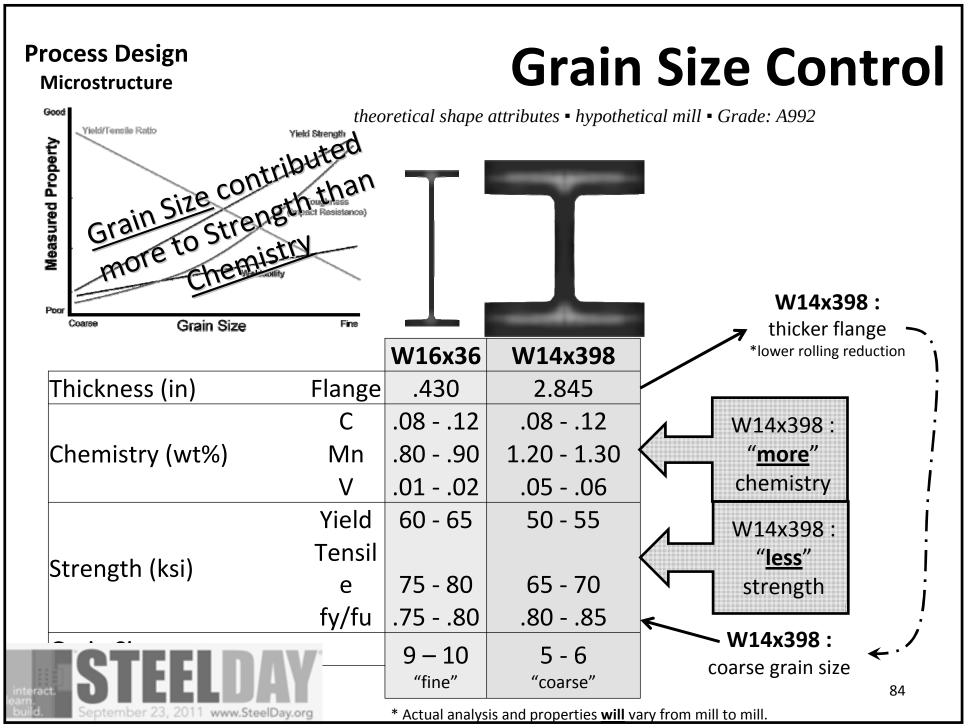
Austenitic Temperature Range

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

Grain Size contributed more to Strength than Chemistry

		W16x36	**W14x398**
Thickness (in)	Flange	.430	2.845
Chemistry (wt%)	C	.08 - .12	.08 - .12
	Mn	.80 - .90	1.20 - 1.30
	V	.01 - .02	.05 - .06
Strength (ksi)	Yield	60 - 65	50 - 55
	Tensile	75 - 80	65 - 70
	fy/fu	.75 - .80	.80 - .85
		9 – 10 "fine"	5 - 6 "coarse"

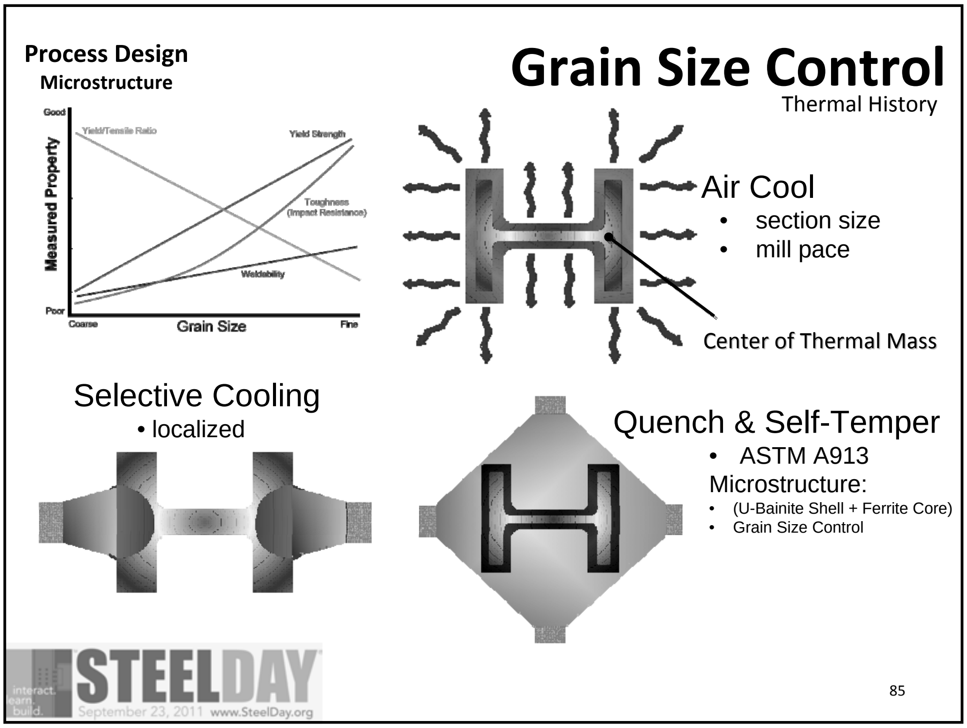
W14x398 : thicker flange
*lower rolling reduction

W14x398 : "**more**" chemistry

W14x398 : "**less**" strength

W14x398 : coarse grain size

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



Process Design
Microstructure

Grain Size Control

Thermal History

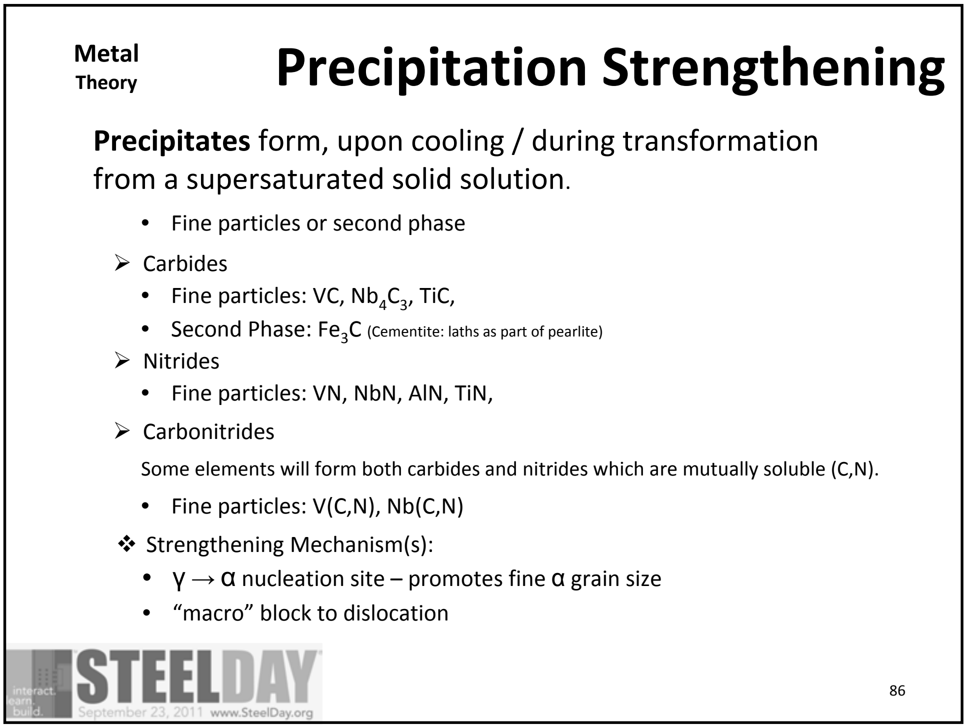
Air Cool
- section size
- mill pace

Center of Thermal Mass

Selective Cooling
- localized

Quench & Self-Temper
- ASTM A913

Microstructure:
- (U-Bainite Shell + Ferrite Core)
- Grain Size Control



Metal
Theory

Precipitation Strengthening

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

- Fine particles or second phase

➢ Carbides
- Fine particles: VC, Nb_4C_3, TiC,
- Second Phase: Fe_3C (Cementite: laths as part of pearlite)

➢ Nitrides
- Fine particles: VN, NbN, AlN, TiN,

➢ Carbonitrides

Some elements will form both carbides and nitrides which are mutually soluble (C,N).

- Fine particles: V(C,N), Nb(C,N)

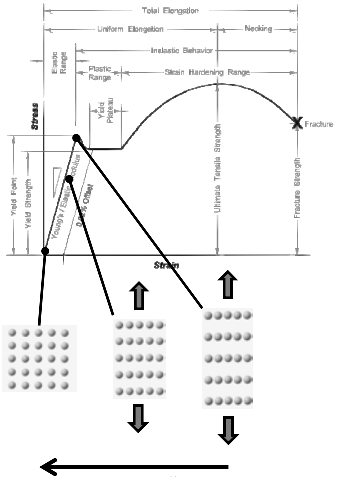
❖ Strengthening Mechanism(s):
- $\gamma \rightarrow \alpha$ nucleation site – promotes fine α grain size
- “macro” block to dislocation

Process Design

Mechanical Response

Young's / Elastic Modulus

{ Ferritic State }



Remove stress, will return to
original shape
ELASTIC BEHAVIOR

"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 => 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

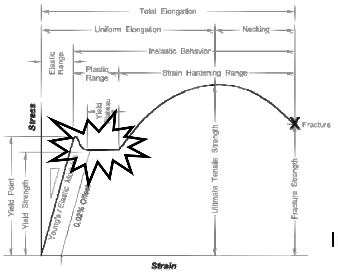
Temperature Dependent

Process Design

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. ⇧ Strain Rate = ⇧ 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**

⇦ can give variability in "results" due .2% offsets

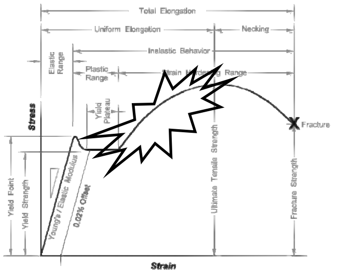
Yield Strength: If no sharp point, virtually impossible to determine exact point when plastic deformation occurs: <u>Yield Strength</u> = occurs at .2% deformation (offset from elastic modulus).

Process Design

Mechanical Response

Strain Hardening

{ Ferritic State }



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

   << remove from further slip >>

2. Dislocations pinned by solute atoms

   << remove from further slip >>

Increasing Stress required to create new dislocations and slip on multiple crystal "packing" axes (not only the weak axis)

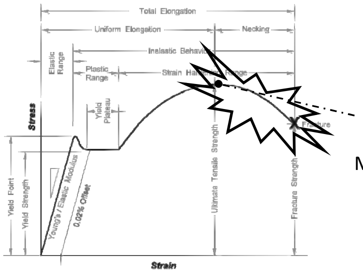
Uniform Cross-Sectional Volume Reduction / Elongation

Process Design

Mechanical Response

UTS to Failure

{ Ferritic State }



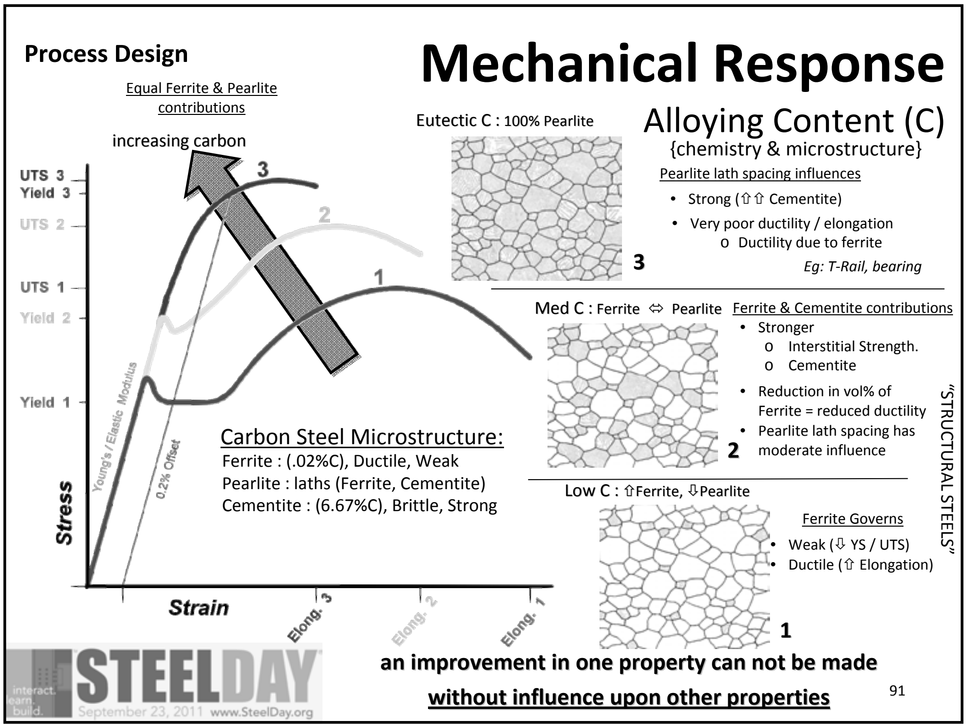
Ultimate Tensile Strength

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

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



Process Design

Mechanical Response

Equal Ferrite & Pearlite contributions

increasing carbon

Carbon Steel Microstructure:

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

Alloying Content (C)

{chemistry & microstructure}

Eutectic C : 100% Pearlite

3

Pearlite lath spacing influences

- Strong (⇧⇧ Cementite)
- Very poor ductility / elongation
  - o Ductility due to ferrite

Eg: T-Rail, bearing

Med C : Ferrite ⇔ Pearlite

2

Ferrite & Cementite contributions

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

"STRUCTURAL STEELS"

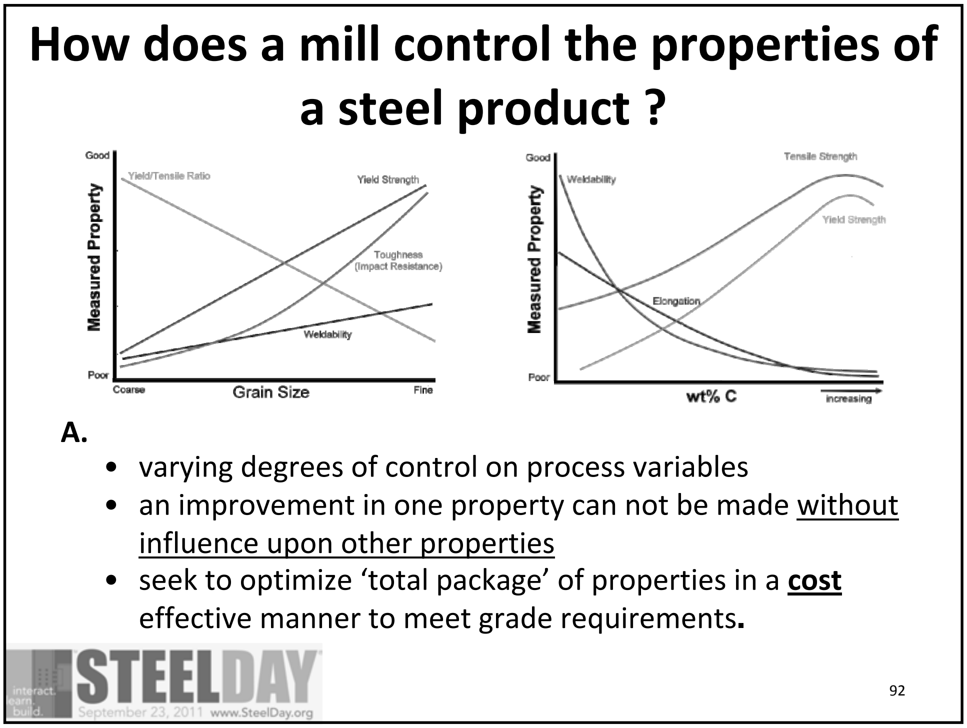
Low C : ⇧Ferrite, ⇩Pearlite

1

Ferrite Governs

- Weak (⇩ YS / UTS)
- Ductile (⇧ Elongation)

an improvement in one property can not be made <u>without influence upon other properties</u>



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

A.

- varying degrees of control on process variables
- an improvement in one property can not be made <u>without influence upon other properties</u>
- seek to optimize 'total package' of properties in a **<u>cost</u>** 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)

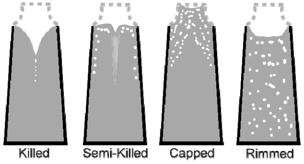
- **Exactly Same Values ?**
  - **✗ No**
- **"Nominally" Same Values ?**
  - **✓ Yes**

MTR Variability

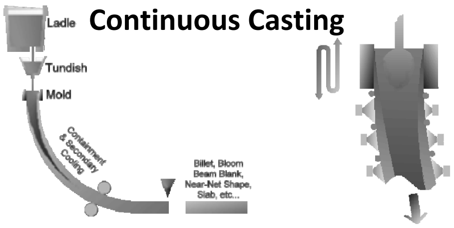
Chemical Analysis

Casting Method(s) strongly influence variability in "Product Check"

Ingot Casting



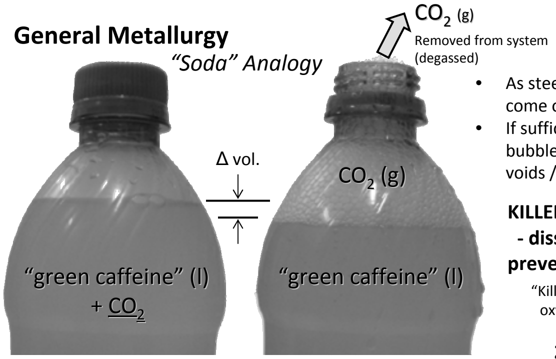
Continuous Casting



	Ingot	Continuous Cast
Killed Nature	Unkilled - to -fully killed **Rimming & Capped** CO evolution (local changes in C levels)	MUST BE FULLY KILLED
Solidification Rate	*SLOW* 8 hrs - 2 days 10 - 40 tons	*FAST* 45 - 60 min 80 - 120 tons
Segregation	can be significant (C, S, P)	Minimal
"Heat"/Batch Separation	Single Heat in Mold	Sequenced Heats

General Metallurgy

"Soda" Analogy



"Killed"

- As steel cools ⇨ solidifies, dissolved gases <u>H</u>, <u>O</u>, <u>N</u> come out of solution.
- If sufficient <u>O</u>: <u>O</u> reacts with <u>C</u> in liquid forming $CO_{(g)}$ bubble. Results in local reduction in carbon content + voids / bubbles trapped in solid steel. (<u>UNKILLED</u>)

KILLED STEEL:

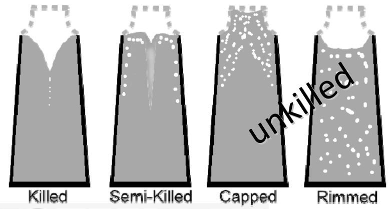
- dissolved oxygen content low enough to prevent $CO_{(g)}$ evolution during solidification.

"Killing" accomplished by removing / "tying-up" dissolved oxygen through reaction with metals possessing a high chemical affinity for oxygen.

$$2\underline{Al} + 3\underline{O} = Al_2O_3\ (s) \quad | \quad \underline{Si} + 2\underline{O} = SiO_2\ (s)$$

⇨ **loss of CO_2 solubility** ⇨

Ingot Casting



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)

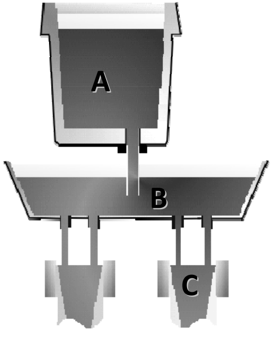
Fast Cooling: Low (microscopic) Segregation
Chemically Homogeneous

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**

MTR Variability

Tension Test Results

ASTM A6/A6M – 10a

Appendix X2. Variation of Tensile Properties in Plates and Shapes

X2.1

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

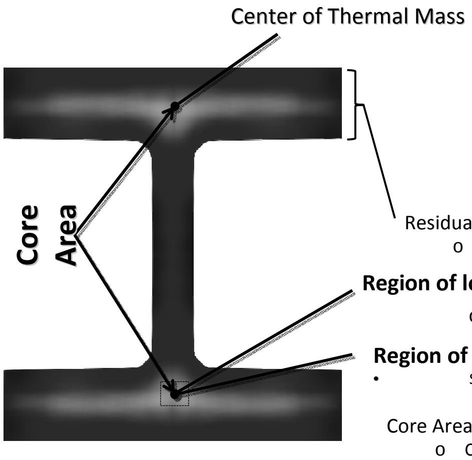
X2.2

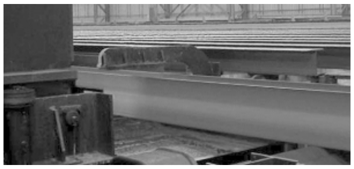
- *<u>Expected variability</u>: “one standard deviation equals approximately 4% of required tensile strength, 8% of required yield strength, and 3% of required elongation.”.*

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

MTR Variability

“Thick” W Shapes





bar leaving “hot” side of mill, entering cooling bed

SDI-SRD, Columbia City, IN

Residual Heat: variable thermal profile across thickness

- leads to variable grain size across thickness (grain growth)

Region of low reduction ratio

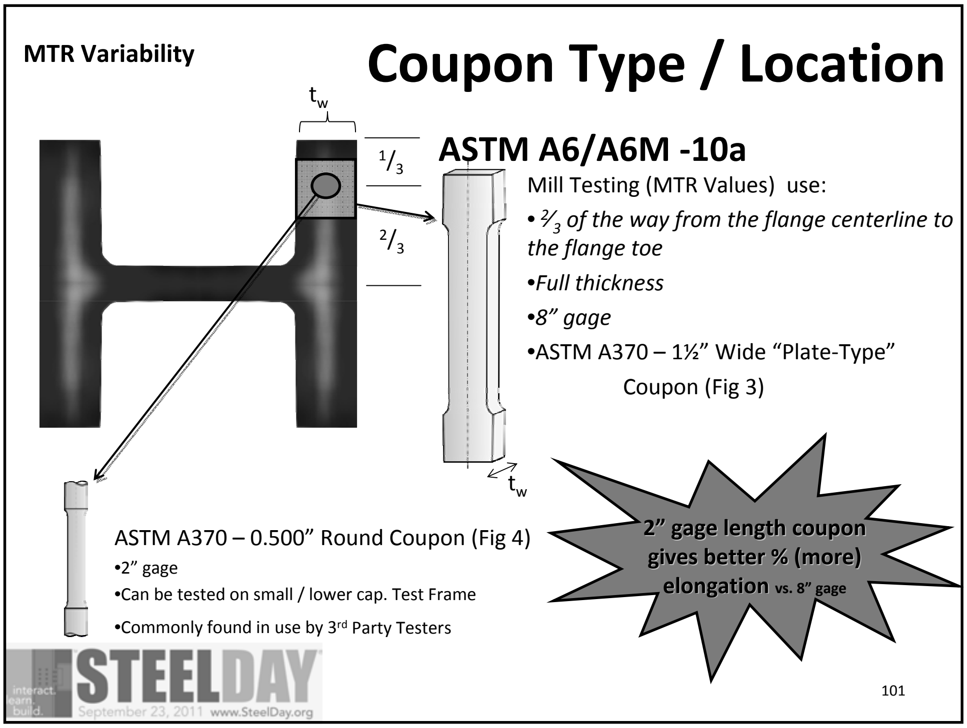
- coarse grain size

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”):

- Coarsest Grain Size / potentially most segregated
- Lowest Toughness



MTR Variability

Coupon Type / Location

ASTM A6/A6M -10a

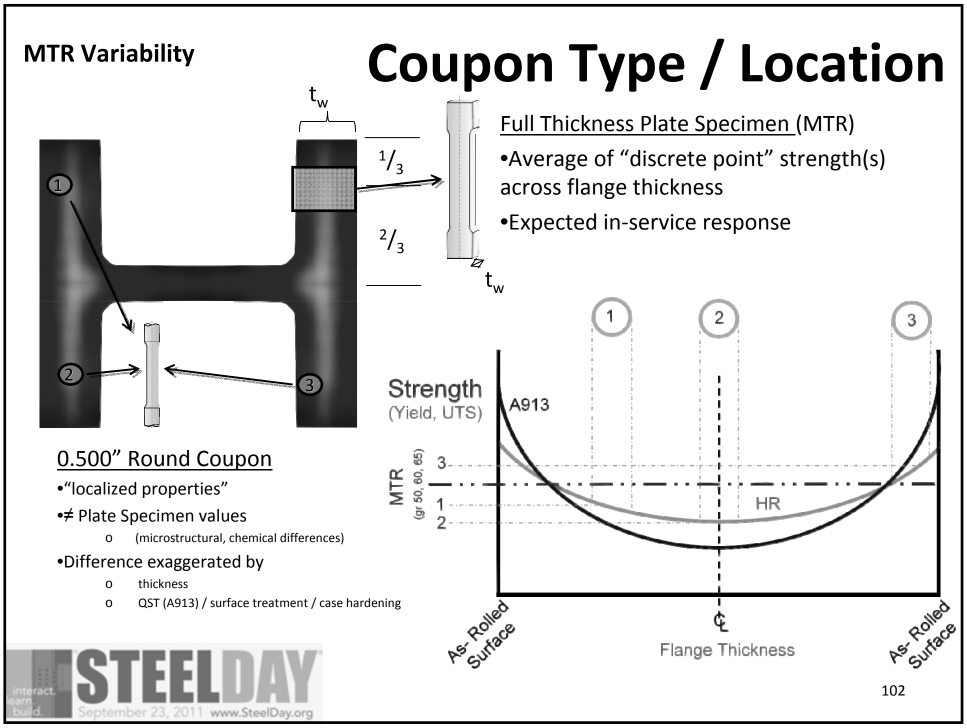
Mill Testing (MTR Values) use:

- *⅔ of the way from the flange centerline to the flange toe*
- *Full thickness*
- *8" gage*
- ASTM A370 – 1½" Wide "Plate-Type" Coupon (Fig 3)

ASTM A370 – 0.500" Round Coupon (Fig 4)

- 2" gage
- Can be tested on small / lower cap. Test Frame
- Commonly found in use by 3rd Party Testers

2" gage length coupon gives better % (more) elongation vs. 8" gage



MTR Variability

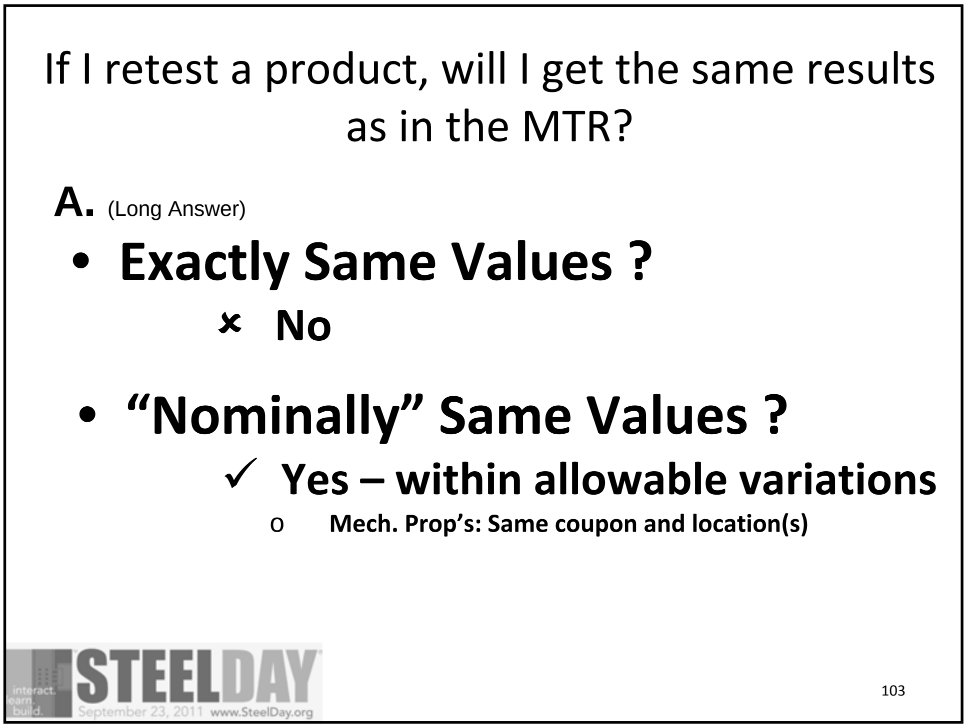
Coupon Type / Location

<u>Full Thickness Plate Specimen</u> (MTR)

- Average of "discrete point" strength(s) across flange thickness
- Expected in-service response

<u>0.500" Round Coupon</u>

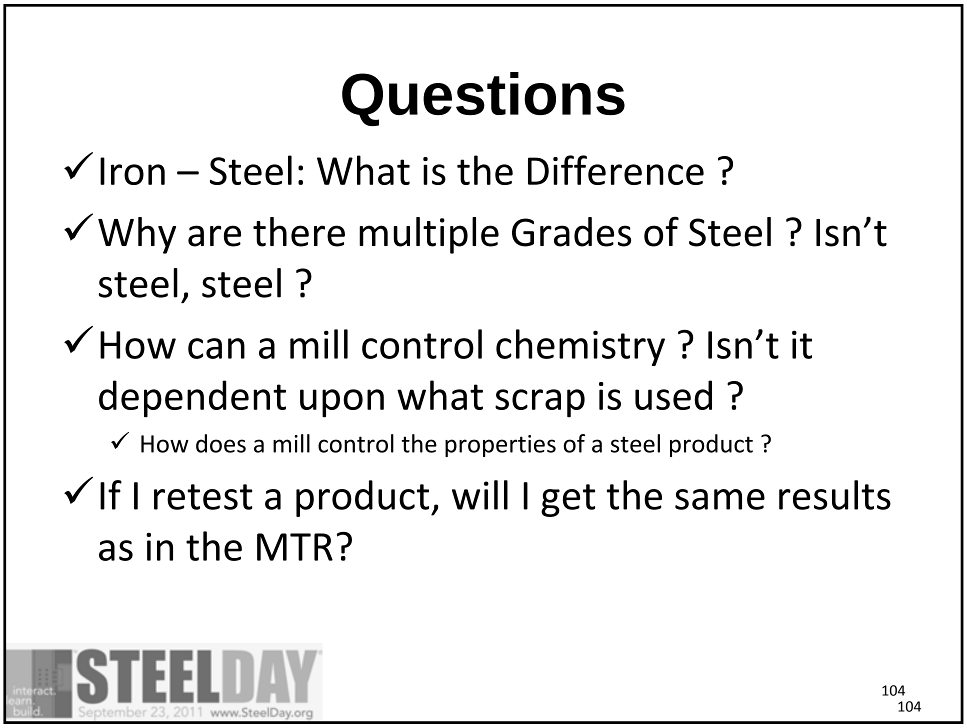
- "localized properties"
- ≠ Plate Specimen values
  - (microstructural, chemical differences)
- Difference exaggerated by
  - thickness
  - QST (A913) / surface treatment / case hardening



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

A. (Long Answer)

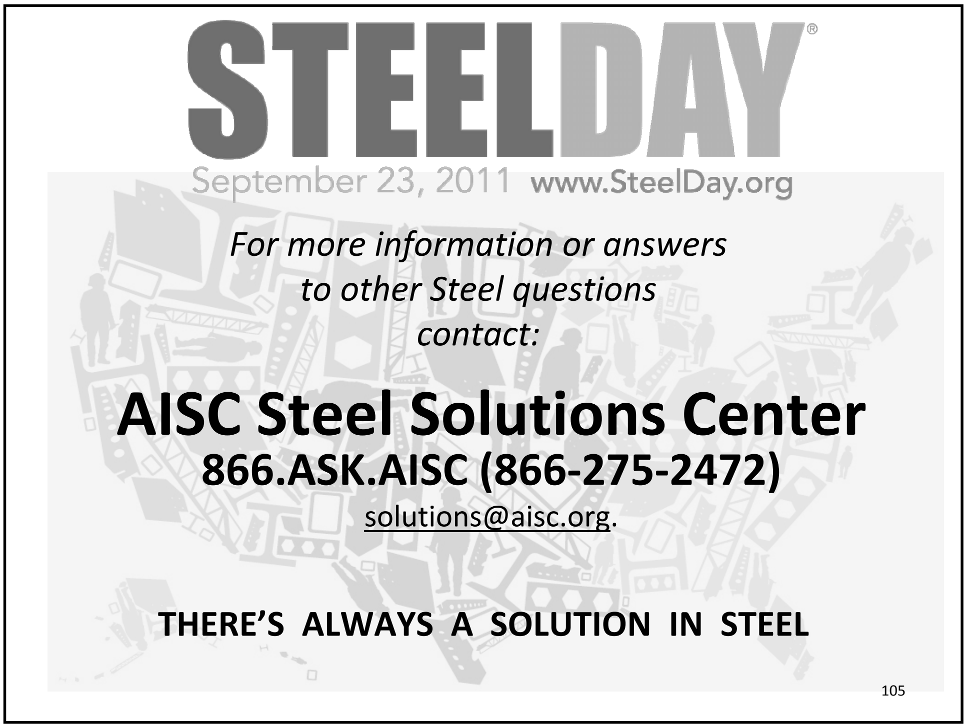
- **Exactly Same Values ?**
  - × **No**
- **"Nominally" Same Values ?**
  - ✓ **Yes – within allowable variations**
    - o **Mech. Prop's: Same coupon and location(s)**



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?

104



STEELDAY®

September 23, 2011 www.SteelDay.org

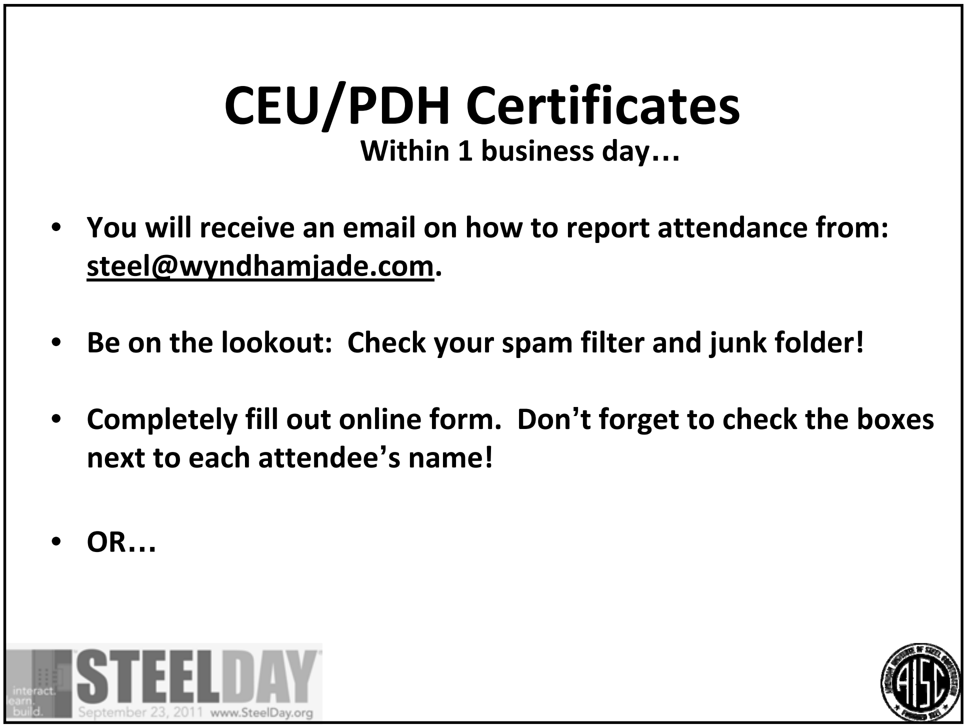
For more information or answers to other Steel questions contact:

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…**

interact. learn. build. STEELDAY September 23, 2011 www.SteelDay.org

CEU/PDH Certificates

Access available in 24 hours…

- **Go to:**
  http://www.wynjade.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
The *NEW* 14th Edition Manual/2010 Specification Seminar

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

AISC eLearning

Over 80 hours of presentations available anytime, online.

CEUs/PDHs are available.

www.aisc.org/elearning

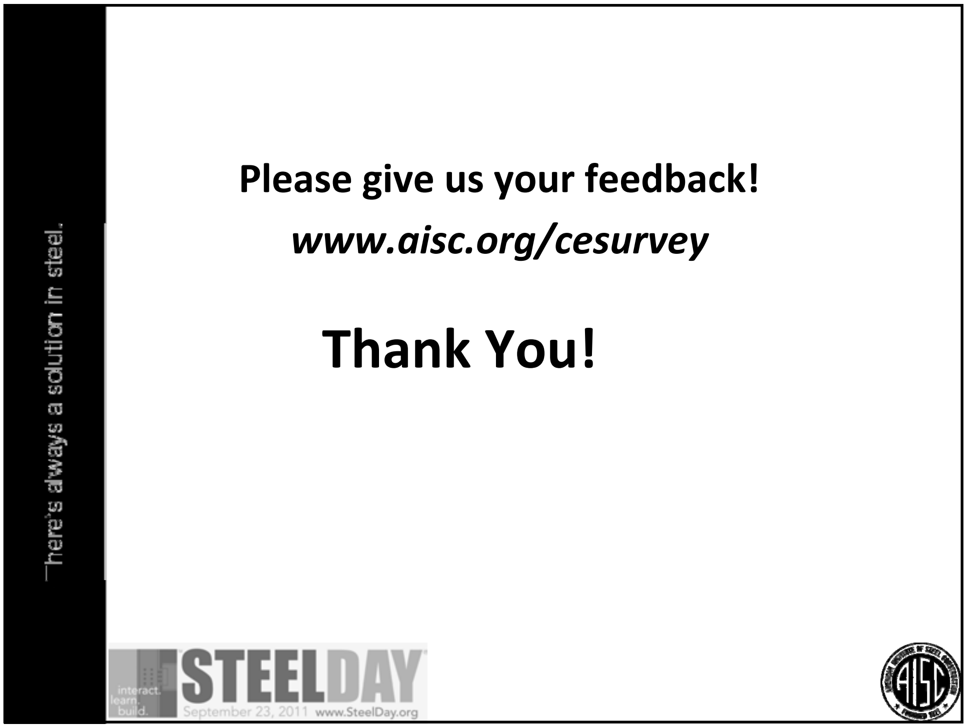
AISC Live Webinars

More live webinars coming soon including

December 8, 2011: New Composite Design Provisions

www.aisc.org/webinars

interact. learn. build. STEELDAY September 23, 2011 www.SteelDay.org



There's always a solution in steel.

Please give us your feedback!

www.aisc.org/cesurvey

Thank You!

interact. learn. build. STEELDAY September 23, 2011 www.SteelDay.org