

Basic Metallurgy for Welding AND Fabricating Professionals

Course Objectives:

- To understand metals and their properties
- To understand effects of various alloying elements on properties and Iron Carbide diagram
- To understand various Carbon Steels & their Heat Treatment process
- To understand different types of low alloy steels and their Heat Treatment Process
- to understand Stainless Steel, types of Stainless Steel

Course Objectives:

- To understand various types of Heat Treatment Process such as Normalising, Annealing, Quenching, Tempering, Surface Hardening & Stress Relieving
- to understand Cracking in Steels
- To understand Destructive Testing specially (Tensile, Impact & Bend Test)
- To understand Forging, Casting, Rolling & welding Process

Course Objectives:

- Weldability of steels
- Fundamental of High Alloy Steel
- Solidification of Metals & Alloys
- To understand how to check test certificate

Module – 1: Introduction to Metals, types and their Properties

Metal

- Metal is a chemical element that is a good conductor of both electricity and heat and forms cations and ionic bonds with non-metals. In chemistry, a metal (Ancient Greek metallon) is an element, compound, or alloy characterized by high electrical conductivity.

Metal

- In a metal, atoms readily lose electrons to form positive ions (cations). Those ions are surrounded by delocalized electrons, which are responsible for the conductivity. The solid thus produced is held by electrostatic interactions between the ions and the electron cloud, which are called metallic bonds

Metal and Non-Metal

Metals

- ☐ Strong
- ☐ Malleable and Ductile
- ☐ React with oxygen to form basic oxides
- ☐ Sonorous
- ☐ High melting and Boiling points
- ☐ Good Conductor of electricity
- ☐ Good conductor of Heat
- ☐ Mainly solid at room temp. except Mercury-liquid at room temp.
- ☐ Shiny when polished
- ☐ When they Ions, the Ions are positive
- ☐ High density

Non-Metals

- ☐ Brittle
- ☐ Brittle
- ☐ React with Oxygen to form acidic oxides
- ☐ Dull sound when hit with Hammer
- ☐ Low melting and Boiling points
- ☐ Poor conductors of electricity
- ☐ Poor conductor of Heat
- ☐ Solids, Liquids and Gases at room temp.
- ☐ Dull looking
- ☐ When they form Ions, the Ions are negative, except Hydrogen (Positive)
- ☐ Low density

Metal and Non-Metal

Metals

- ☐ Calcium
- ☐ Potassium
- ☐ Lead
- ☐ Copper
- ☐ Aluminium
- ☐ Zinc
- ☐ Lithium

Non-Metals

- ☐ Sulphur
- ☐ Oxygen
- ☐ Chlorine
- ☐ Hydrogen
- ☐ Bromine
- ☐ Nitrogen
- ☐ Helium

Uses of Metals

- They are made into jewellery due to their hard and shiny appearance
- They are used to make pans, since they are good conductors of heat
- They are used in electric cables, because they are malleable, ductile and good conductors of electricity

Uses of Metals

- They are so strong to build bridges and scaffolding
- They make a ringing sound, sonorous, hence they are used in bell making.

Uses of Non- Metals

- Oxygen- used for Respiration, for burning rocket fuels.
- Nitrogen-used for manufacturing ammonia and urea
- Diamond- used as a gem
- Silicon- used for manufacturing of glass
- Chlorine-used for Disinfecting water

Uses of Non- Metals

- Graphite- used as an electrodes
- Iodine- used as an antiseptic
- Hydrogen- used in oxy Hydrogen torch, For hydrogenation of vegetable oils
- Helium-used for filling balloons
- Neon-used for illuminating advertisement signs

Ferrous and Non-ferrous metal

- **Ferrous Metal:**

All metals that contain any amount of iron in its basic form is considered a ferrous metal. Because of this, the only ferrous metallic element in the periodic table is iron. Many metals, such as steel, have a percentage of iron, which means they are a ferrous metal. A few examples of ferrous metals are stainless steel, carbon steel and wrought iron.

Ferrous and Non-ferrous metal

- **Non-ferrous metal:**

Nonferrous metals are the opposite of ferrous and do not contain any iron. Alloy metals that are free of iron are also considered non-ferrous. All the metals in the periodic table, with the exception of iron, are non-ferrous. A few examples of non-ferrous metals are aluminum, brass, copper and tungsten steel.

Chemical properties of Metal decides-mechanical properties

- Strength
- Ductility
- Hardness
- Toughness
- Fatigue Resistance
- Corrosion Resistance
- Life of Equipment

M1: Act. 1

Which material has the best corrosion properties and why?

Module – 2 : Effects of various alloying elements and Iron Carbide diagram

Steel

- Steel is an alloy mainly containing Iron(Fe), but also contain small amount of Carbon, Sulphur, Manganese, phosphorous and Silicon

Carbon and Alloy Steels

All these steels are alloys of Iron (Fe) and Carbon(c)

- ❖ Plain carbon steels (less than 2% carbon and negligible amounts of other residual elements)
 - Low Carbon(Less than 0.3% carbon)
 - Med. Carbon (0.3% to 0.6%)
 - High Carbon(0.6% to 0.95%)
- ❖ Low Alloy Steel
- ❖ High Alloy Steel
- ❖ Stainless Steels (Corrosion- resistant Steels)- contain atleast 10.5% Chromium

Steel Making Process

- Primary Steelmaking:

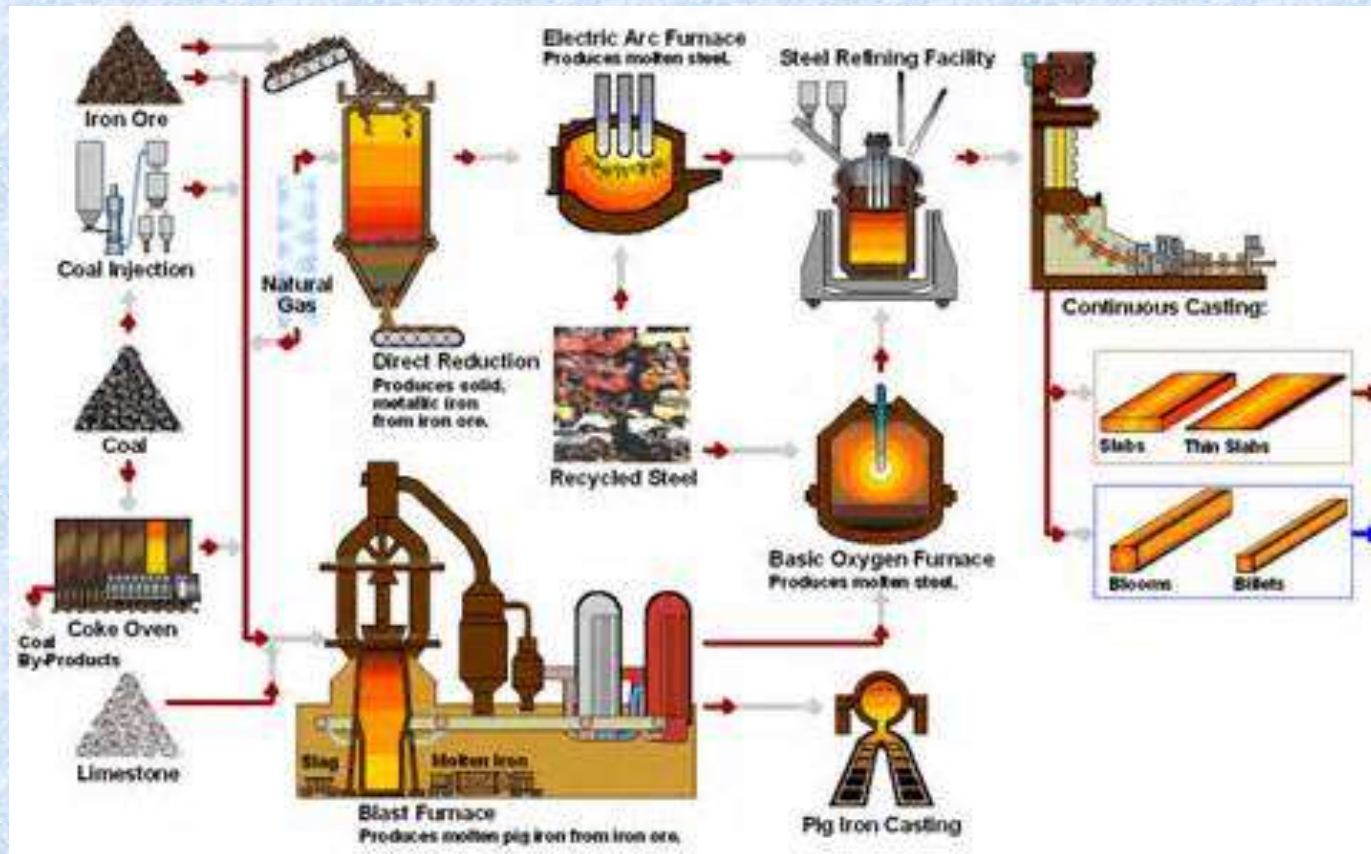
Basic oxygen steelmaking which has liquid pig-iron from the blast furnace and scrap steel as the main feed material

Electric arc Furnace (EAF)steelmaking which uses scrap steel or direct reduced iron (DRI)as the main feed material

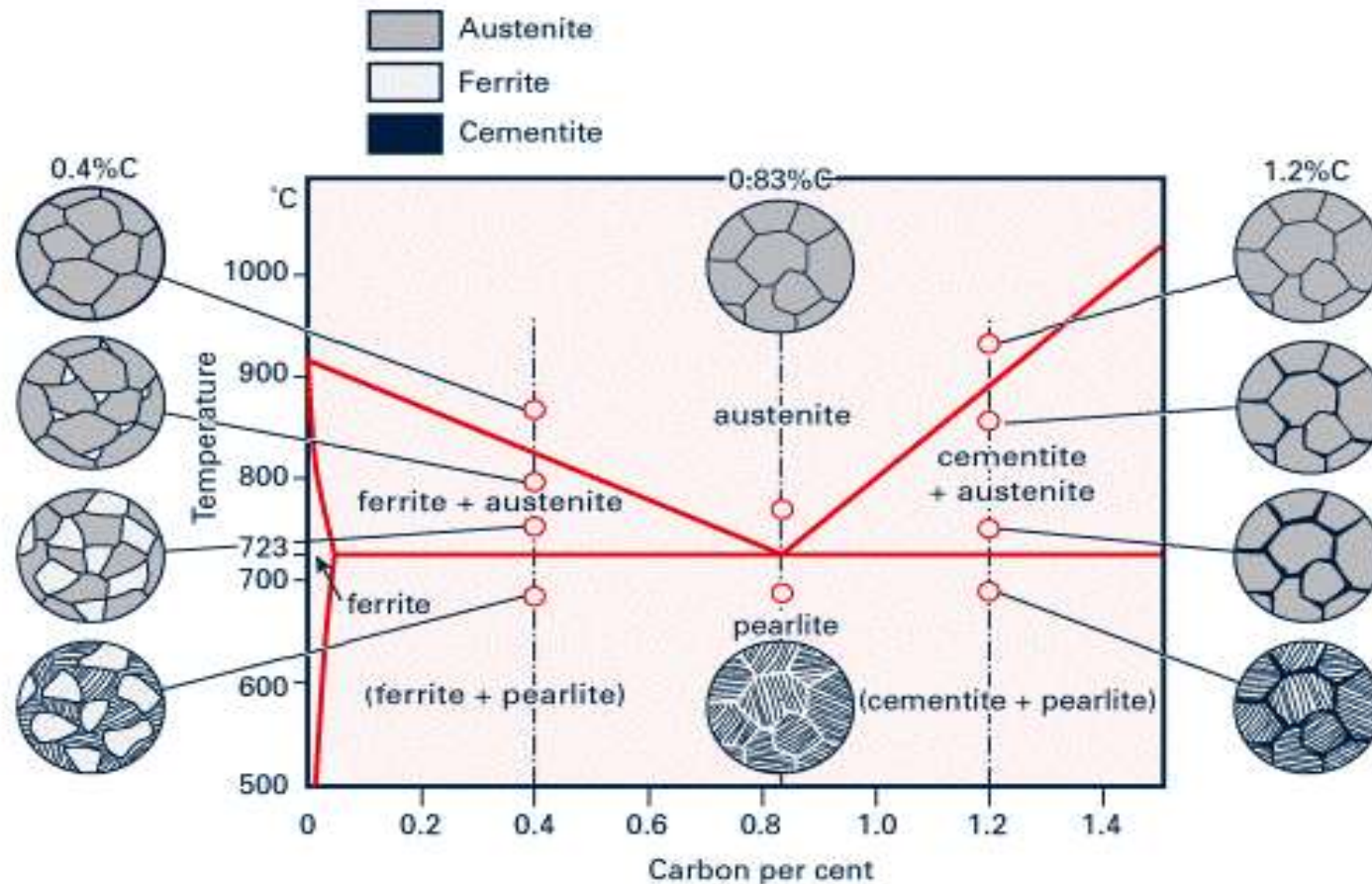
- Secondary Steelmaking

Electro slag remelting (ESR) also known as electroflux remelting is a process of remelting and refining steel and other alloys for mission critical application

Steel making Process



Iron Carbide Diagram



Phases in Iron-Carbide Diagram

➤ α -ferrite - solid solution of C in BCC Fe

- Stable form of iron at room temperature.
- The maximum solubility of C is 0.022 wt%
- Transforms to FCC γ -austenite at 912 °C

➤ γ -austenite - solid solution of C in FCC Fe

- The maximum solubility of C is 2.14 wt %.
- Transforms to BCC δ -ferrite at 1395 °C
- Is not stable below the eutectic temperature (727 °C) unless cooled rapidly

Phases in Iron-Carbide Diagram

➤ δ -ferrite solid solution of C in BCC Fe

- The same structure as α -ferrite
- Stable only at high T, above 1394 °C
- Melts at 1538 °C

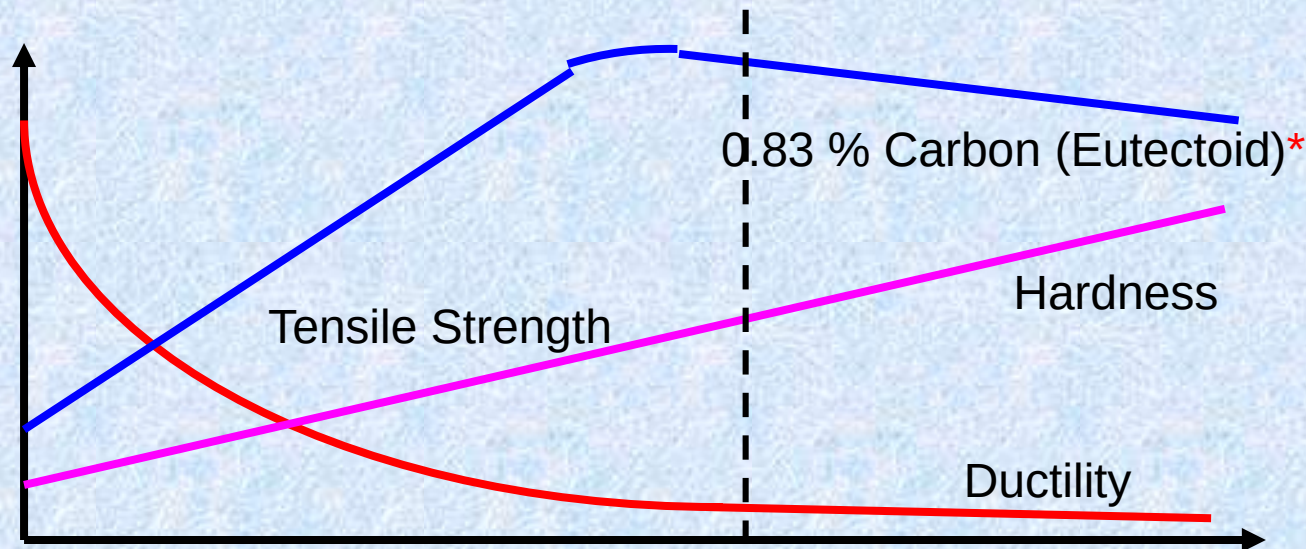
➤ Fe_3C (iron carbide or Cementite)

- This intermetallic compound is metastable, it remains as a compound indefinitely at room T, but decomposes (**very slowly, within several years**) into α -Fe and C (graphite) at 650 - 700 °C

➤ Fe-C liquid solution

Effect of Carbon in the Properties of Iron

- Increasing the carbon content will increase the strength, but will also increase greatly the risk of formation of Martensite



M2: Act. 2

Which Structure forms when steel is cooled rapidly from Austenite Stage, leaving insufficient time for carbon to form Pearlite and why?

Module – 3 : different types of Carbon Steels and their Heat Treatment

Steel

Steel is most widely used in Industries. Steel is an alloy containing mainly Iron(Fe), but also contain small amount of:

- Carbon
- Manganese
- Phosphorous
- Sulphur
- Silicon

Carbon and alloy Steels

All of these steels are alloys of Fe and C

- ❖ Plain carbon steels (less than 2% carbon and negligible amounts of other residual elements)
 - Low carbon (less than 0.3% carbon)
 - Med carbon (0.3% to 0.6%)
 - High carbon (0.6% to 0.95%)
- ❖ Low alloy steel
- ❖ High Alloy Steel
- ❖ Stainless steels (corrosion resistant steels)
 - ✓ Contain at least 12% Chromium

Types of Steel

- Steel is an alloy containing mainly Iron (Fe), but also contain small amount of carbon, Manganese, Phosphorous, Sulphur and Silicon.

<u>Common name</u>	<u>Carbon Content</u>	<u>Typical Use</u>	<u>Weldability</u>
Low carbon steel	0.15 % max	Welding electrodes, Special plate, sheet & Strip	Excellent
Mild Steel	0.15% - 0.30%	Structural Material, Plate & Bar	Good
Medium Carbon Steel	0.30% - 0.50%	Machinery Parts	Fair (Preheat and Frequent post heat is required)
High Carbon Steel	0.50% - 1.00%	Springs, Dyes and Rails	poor

Classification of Steel based on Degrees of De-Oxidation

Fully Killed Steel

- Fully killed steel is steel that has had all of its oxygen content removed and is typically combined with an agent before use in applications, such as casting.
- Ferrosilicon alloy added to metal that combines with oxygen & form a slag leaving a dense and homogenous metal.

Fully Killed Steel



Vacuum Deoxidized Steel

- Vacuum deoxidation is a method which involves using a vacuum to remove impurities.
- Oxygen removed from the molten steel without adding an element.
- A portion of the carbon and oxygen in steel will react, forming carbon monoxide.
- Result, the carbon and oxygen levels fall within specified limits

Vacuum Deoxidized Steel



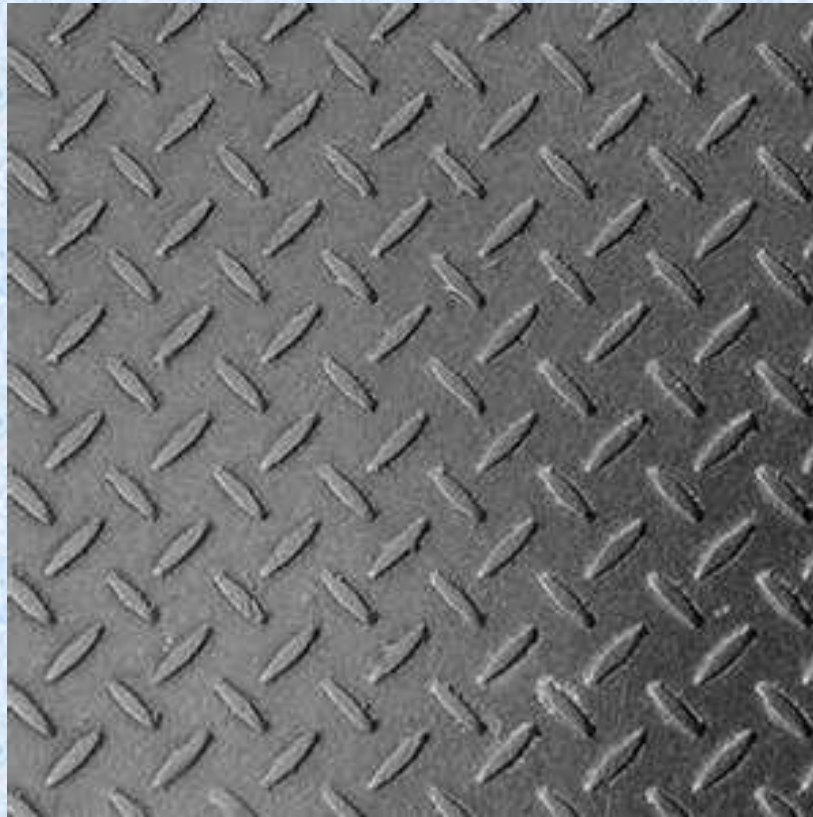
Rimmed Steel

- Rimmed steel is a type of low-carbon steel that has a clean surface and is easily bendable.
- Rimmed steel involves the least deoxidation.
- Composition : 0.09% C, 0.9% Mg + Residual
- Weld Ability: Weld pool required to have added deoxidant via filler metal.

Semi Killed Steel

- Semi-killed steel is mostly deoxidized steel, but the carbon monoxide leaves blowhole type porosity distributed throughout the ingot.
- Semi-killed steel is commonly used for structural steel
- Carbon content ranges between 0.15 to 0.25% carbon, because it is rolled, which closes the porosity.
- In semi-killed steel, the aim is to produce metal free from surface blowhole and pipe.

Semi Killed Steel



AISI- SAE Classification System

AISI XXXX

American Iron and Steel Institute(AISI)

- ❖ Classifies alloys by Chemistry
- ❖ 4 digit number
 - ✓ 1st number is the major alloying element
 - ✓ 2nd number designates the subgroup alloying element OR the relative percent of primary alloying element.
 - ✓ Last two numbers approximate amount of carbon (expresses in 0.01⁰%)

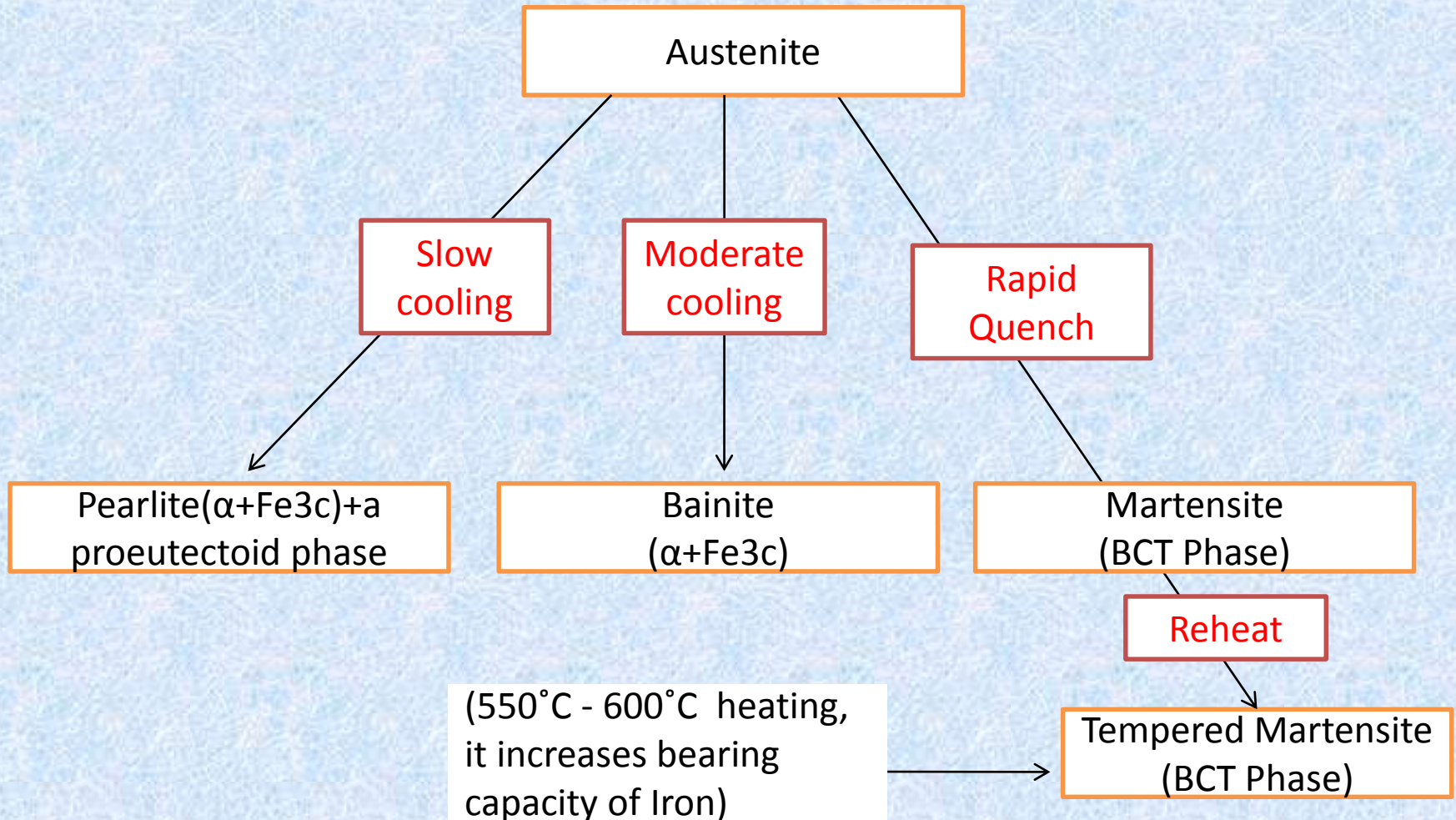
AISI-SAE Classification System

- Letter prefix to designate the process used to produce the steel
 - ✓ E= electric furnace
 - ✓ X=indicates permissible variations
- If a letter is inserted between the 2nd and 3rd number
 - ✓ B= Boron has been added
 - ✓ L=lead has been added
- Letter suffix
 - ✓ H= when hardenability is a major requirement
- Other designation organisations
 - ✓ ASTM and MIL

Major Classification of Steel

<u>SAE</u>	<u>Type</u>	<u>Examples</u>
• 1XXX	Carbon steels	2350
• 2XXX	Nickel steels	2550
• 3XXX	Nickel-Chromium steels	4140
• 4XXX	Molybdenum steels	1060
• 5XXX	Chromium steels	
• 6XXX	Chromium- Vanadium steels	
• 7XXX	Tungsten steels	
• 8XXX	Nickel Chromium Molybdenum steels	
• 9XXX	Silicon Manganese steels	

Heat Treatment of Steel



What is the purpose of Silicon in Steel?

Module – 4: Low Alloy Steels and their Heat treatment

Low Alloy Steel

- Low alloy steel contain minor additions of other elements such as Nickel, Chromium, Vanadium, Columbium, Aluminium, Molybdenum and Boron.
- These elements changes the mechanical properties to a great extent.

Classification of Low Alloy Steel

- High strength Low Alloy, Structural Steel
- Automotive and Machinery steels
- Steel for Low Temperature service
- Steels for elevated Temperature Service

Steel for Low Temperature Service

- Steel used for low temperature service, below 0°C also known as **cryogenic service**.
- It result into **brittle** of metal.
- yield and tensile strengths of metals that crystallize in the body-centered cubic from iron, molybdenum, vanadium and chromium depend greatly on temperature.
- These metals display a loss of ductility in a narrow temperature region below room temperature.

Steels for elevated Temperature Service

- Stainless steels have good strength and good resistance to corrosion and oxidation at elevated temperatures.
- Stainless steels are used at temperatures up to 1700° F for 304 and 316 and up to 2000 F for the high temperature stainless grade 309(S) and up to 2100° F for 310(S).
- Stainless steel is used extensively in heat exchangers, super-heaters, boilers, feed water heaters, valves and main steam lines as well as aircraft and aerospace applications.

Alloy Steel

- Again, elements added to steel can dissolve in iron (solid solution strengthening)
- Increase strength, hardenability, toughness, creep, high temp. resistance
- Alloy steel grouped into low, med and high alloy steels
- High alloy steels would be the stainless steel groups
- Most alloy steels you'll use under the category of low alloy

Alloy Steel

- $> 1.65\% \text{Mn}$, $> 0.60\% \text{Si}$, or $> 0.60\% \text{Cu}$
- Most common alloy elements:
 - ✓ Chromium, nickel, molybdenum, vanadium, tungsten, cobalt boron and copper
- Low alloy: added in small percents ($< 5\%$)
 - ✓ Increase strength and hardenability
- High alloy: Added in large percents ($> 20\%$)
 - ✓ i.e. $> 10.5\% \text{Cr}$ = stainless steel where cr improves corrosion resistance and stability at high or low temp.

Tool steel

- Refers to a variety of carbon and alloy steels that are particularly well suited to be made into tools.
- Characteristics include high hardness resistance to abrasion(excellent wear), an ability to hold a cutting edge, resistance to deformation at elevated temp. (red hardness)
- Tool steel are generally used in a heat treated state.
- High carbon content-very brittle

Alloy used in steel for Heat Treatment Manganese (Mn)

- Combines with sulphur to prevent brittleness
- >1% increases hardenability
- 11% to 14%
 - Increase hardness
 - Good ductility
 - High strain hardening capacity
 - Excellent wear resistance
- Ideal for impact resisting tools

Alloying elements used in steel

Sulphur (S)

- ✓ Imparts brittleness
- ✓ Improves machineability
- ✓ Okay, if combined with Mn.
- ✓ Some free-machining steels contain 0.08% to 0.15% S
- ✓ Examples of S alloys:
 - 11XX-sulphurized (free-cutting)

Alloying elements used in steel

Nickel (Ni)

- Provides strength, stability and toughness

Examples of Ni alloys:

- 30xx-Nickel (0.70%), Chromium (0.70%)
- 31xx-Nickel (1.25%), Chromium (0.60%)
- 32xx nickel (1.75%), chromium (1.00%)
- 33xx-Nickel (3.50%), Chromium (1.50%)

Alloying elements used in steel

Chromium (Cr)

- Usually $<2\%$
- Increase hardenability and strength
- Offers corrosion resistance by forming stable oxide surface
- Typically used in combination with Ni and Mo
 - 30xx-Nickel (0.70%), Chromium (0.70%)
 - 5xxx-chromium alloys
 - 6xxx-chromium-vanadium alloys
 - 41xx-chromium-molybdenum alloys

Alloying elements used in steel

Molybdenum (Mo)

- Usually $<0.3\%$
- Increase hardenability and strength
- Mo-carbides help increase creep resistance at elevated temp.
 - Typical application is hot working tools.

Alloying elements used in steel

Vanadium

- Usually 0.03% to 0.25%
- Increase strength
- Without loss of ductility

Tungsten (W)

- Helps to form stable carbides
- Increase hot hardness
 - Used in tool steels

Alloying elements used in steel

Copper (Cu)

- 0.10% to 0.50%
- Increase corrosion resistance
- Reduced surface quality and hot working ability
- Used in low carbon sheet steel and structural steels

Silicon (Si)

- About 2%
- Increase strength without loss of ductility
- Enhance magnetic properties

Alloying elements used in steel

Boron (B)

- For low carbon steels, can drastically increase hardenability
- Improves machineability and cold forming capacity

Aluminium (Al)

- Deoxidizer
- 0.005% to 0.010%
- Produce Al-nitrides during nitriding

Which alloy is/are used in Steel for
High Temp. and why?
and
Which is the purest form of carbon?

Module – 5 : Stainless Steel and types of Stainless Steels

Key points:-A

- Corrosion resistance is imparted by the formation of a passivation layer characterized by :
 - Insoluble chromium oxide film on the surface of the metal-(Cr_2O_3)
 - Develops when exposed to oxygen and impervious to water and air.
 - Layer is too thin to be visible
 - Quickly reforms when damaged
 - Susceptible to sensitization, pitting, crevice corrosion and acidic environments
 - Passivation can be improved by adding nickel, molybdenum and vanadium.

Key Points: B

- Over 150 grades of SS available, usually categorized into 5 series containing alloys similar properties.
- AISI classes for SS:
 - 200 series= chromium, nickel, manganese(austenitic)
 - 300 series=chromium, nickel (austenitic)
 - 400 series=chromium only (ferritic/Martensitic)
 - 500 series=low chromium <12%(martensitic)
 - 600 series=precipitation hardened series (17-7PH, 17-7PH,15-5PH)

Key points C

- SS can be classified by crystal structure (austenitic, ferritic, martensitic)
- Best Corrosion resistance(CR):Austenitic (25% Cr)
- Middle CR: ferritic (15% Cr)
- Least CR: Martensitic (12% Cr), but strongest

Types of Corrosion in Stainless steel

Type of corrosion	Description	To avoid
Intergranular	This type of corrosion results from the precipitation of the Cr carbide, usually on grain boundaries of either ferrite or austenite	%C less than approx. 0.02 because it can't combine with Chromium
Pitting	Small pits develop holes in the passivating film, which set up what is called a galvanic cell, producing corrosion	% Cr greater than 23-24 % Mo greater than 2
Stress Corrosion Cracking	Localized points of corrosion allow stresses initially unable to crack the steel to concentrate sufficiently to now do so. Details of the mechanism are complex and not well understood. The presence of the chlorine ion makes this type of corrosion a problem in salt waters	% Cr greater than 20 % Mo greater than 1

Composition of Martensitic and Ferritic Stainless Steel

AISI type	Carbon %	Mn (Max.)	Silicon (Max.)	Chromium	Nickel	Other
<u>Martensitic</u> 403	0.15	1.00	0.50	11.50-13.00	-	-
<u>Martensitic</u> 410	0.15	1.00	1.00	11.50-13.00	-	-
<u>Martensitic</u> 420	0.15	1.00	1.00	12.00-14.00	-	-
<u>Ferrite</u> 430	0.12	1.00	1.00	14.00-18.00	-	-
<u>Ferrite</u> 446	0.20	1.50	1.00	23.00-27.00	-	0.25% Max N

* Note: sulfur is 0.030 Max.

Which method can reduce
sensitization or Carbide
precipitation of Austenitic Stainless
Steel?

Module – 6 : Heat Treatment & Types of Heat Treatment process

Heat Treatment of Steels

Heat treatment are carried out to change or control the final properties of materials, welded joints and fabrications.

All heat treatment are cycles of 3 elements : heating, holding & cooling.

Type of Heat treatment given to material are:

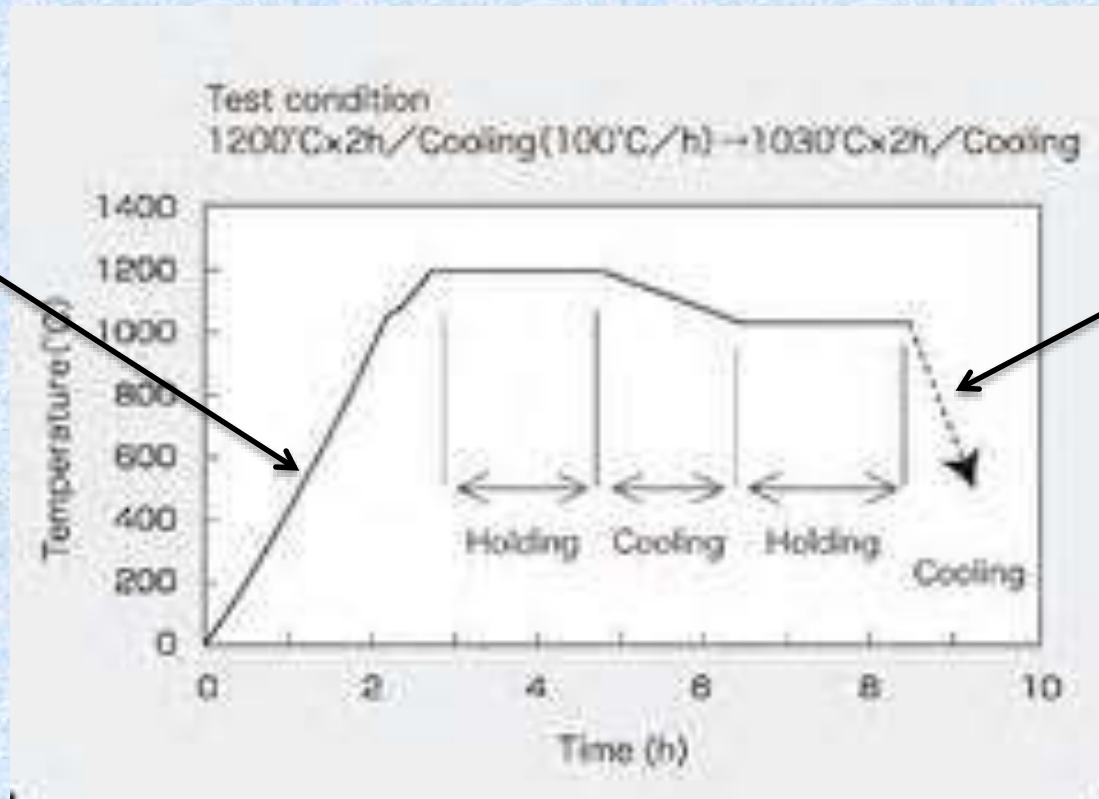
- Stress relieving
- Normalizing
- Annealing
- Solution annealing
- Quenching and tempering
- Case hardening

Heat Treatment Cycle

Variables for heat treatment process must be carefully controlled

Heating
rate

Heating rate will
be slow,
otherwise it
results in cracking



Cooling Rate

Heat Treatment of Steels

Type of Heat Treatment	Soaking Temp.	Soaking Time	Cooling rate	Purpose/Application
<u>Stress relieving</u>	580-700° C	1 Hour per inch of thickness	Furnace cooling up to 300° C	Relieve residual stress/reduce hydrogen levels, improves stability
<u>Normalizing</u>	900-920° C	1.2 minutes per mm	Air Cool	Relieve internal stresses /improve mechanical properties, increase toughness
<u>Annealing</u>	900-920° C	1.2 minutes per mm	Furnace cool	Improve ductility, lower yield stress/ makes bending easier
<u>Solution Annealing only Austenitic SS</u>	1020-1060° C	1.2 minutes per mm	Quench cooling	Prevents carbide precipitation in austenitic steels and avoid the Intergranular corrosion cracking

Hardening

- Heating the steel to a set temp. and then cooling (quenching) it rapidly by plunging it into oil, water or brine.
- Hardening increase the hardness and strength of the steel but makes it less ductile.
- Low carbon steels do not require because no harmful effects result (no transformation for martensitic structure)

Tempering

- To relieve the internal stresses and reduce the brittleness, you should temper the steel after it is hardened.
- Temperature (below its hardening temp.), holding length of time and cooling (in still air)
- Below the low critical point
- Strength hardness and ductility depend on the temp.(during the temp. process).

Case Hardening

- **Case hardening** or **surface hardening** is the process of hardening the surface of a metal object while allowing the metal deeper underneath to remain soft, thus forming a thin layer of harder metal (called the "case") at the surface

Case Hardening

Types of case hardening:

- Carburizing
- Cyaniding
- Flame hardening

Post weld Heat treatment Methods

- Furnace
- Local heat treatment using electric heat blankets
- Muffle furnace
- Circular furnace
- Gas furnace heat treatment
- Induction heating
- Full Annealing

Post weld Heat treatment Methods



Furnace



Muffle furnace



Electric heat blanket

Post weld Heat treatment Methods



Circular Furnace



Gas Furnace heat
furnace



Induction heating



Full Annealing

In Heat Treatment Process which parameters are controlled?

Module – 7 : Various Cracking In Weld

Cracking

When considering any type of cracking mechanism, three elements must always be present:

- **Stress**
Residual stress is always present in a weldment, through unbalanced local expansion and contraction
- **Restraint**
Restraint may be a local restriction, or through plates being welded to each other
- **Susceptible microstructure**
The microstructure may be made susceptible to cracking by the process of welding

Process Cracks

- Hydrogen Induced HAZ Cracking (C/Mn steels)
- Hydrogen Induced Weld Metal Cracking (HSLA steels).
- Solidification or Hot Cracking (All steels)
- Lamellar Tearing (All steels)
- Re-heat Cracking (All steels, very susceptible Cr/Mo/V steels)
- Inter-Crystalline Corrosion or Weld Decay (stainless steels)

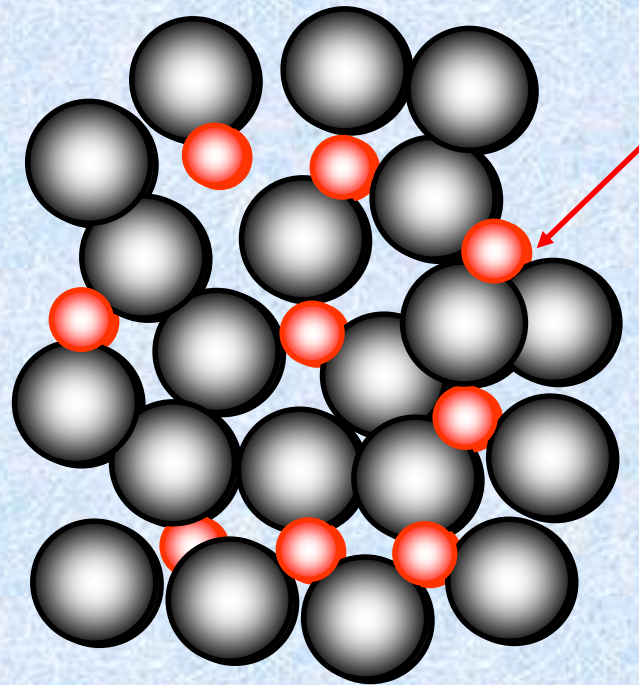
Hydrogen Induced Cold Cracking

Also known as HCC, Hydrogen, Toe, Under bead, Delayed, Chevron Cracking.

Occurs in:

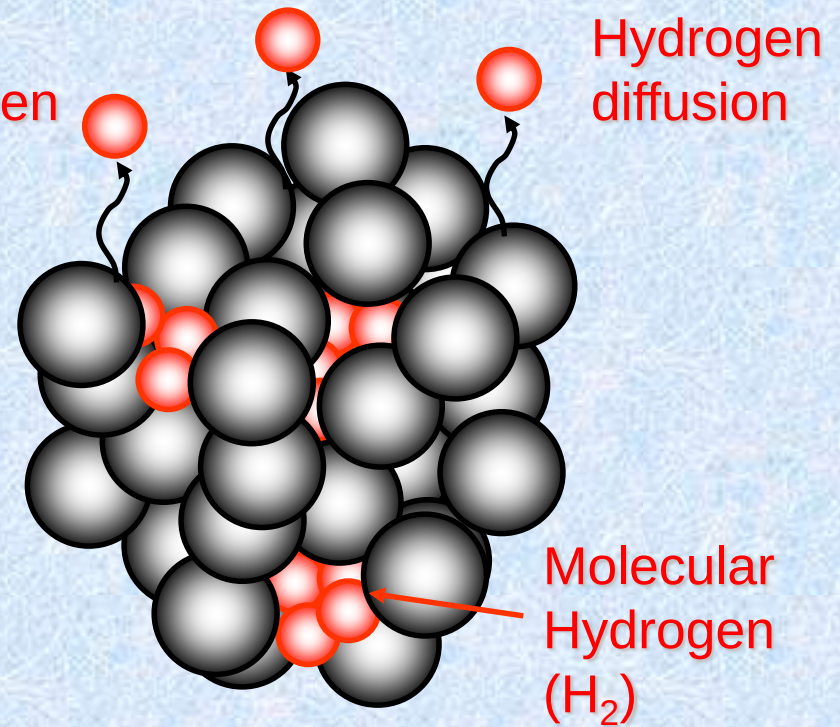
- Carbon Steels
- Carbon-Manganese
- Low, Medium and High Alloy Steels:
 - **Mainly in Ferritic or Martensitic steels.**
 - **Very rarely in Duplex stainless steels,**
 - **Never in Nickel or Copper alloys.**

Hydrogen Induced Cold Cracking



Steel in expanded condition

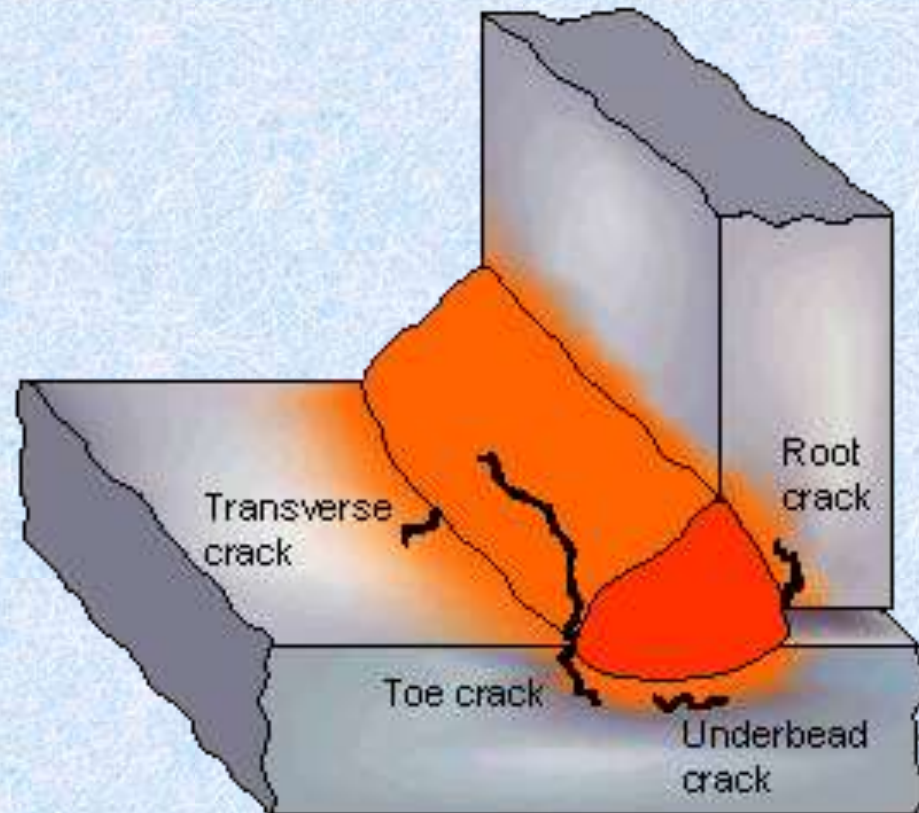
Above 300°C



Steel under contraction

Below 300°C

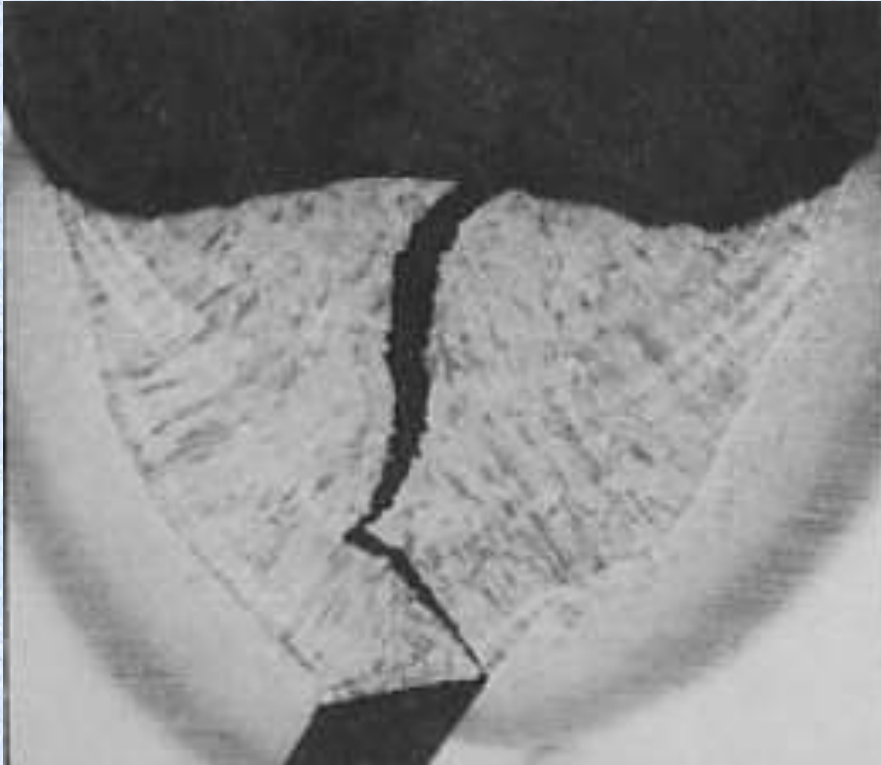
Hydrogen Induced Cold Cracking



Typical locations for Cold Cracking

Hydrogen Induced Cold Cracking

Micro Alloyed Steel



Hydrogen induced weld metal cracking

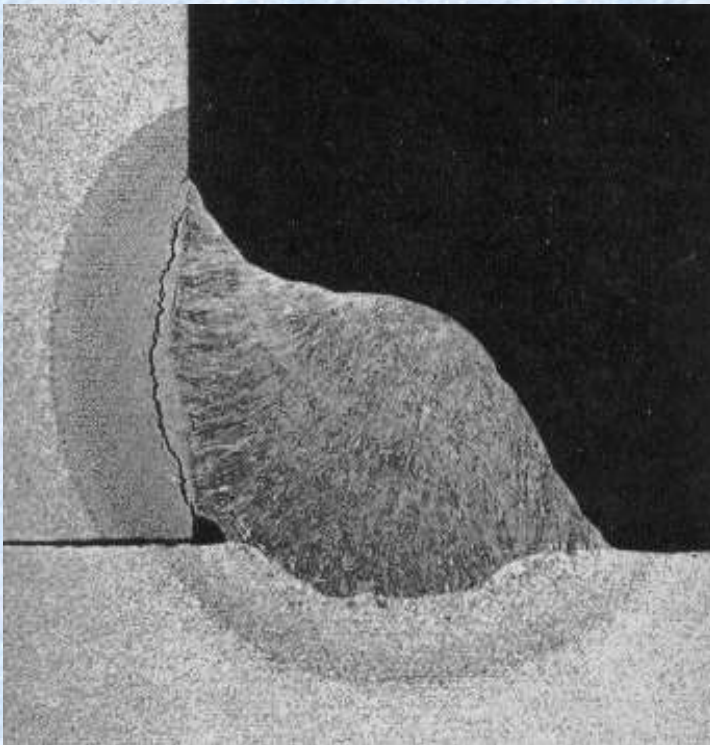
Carbon Manganese Steel



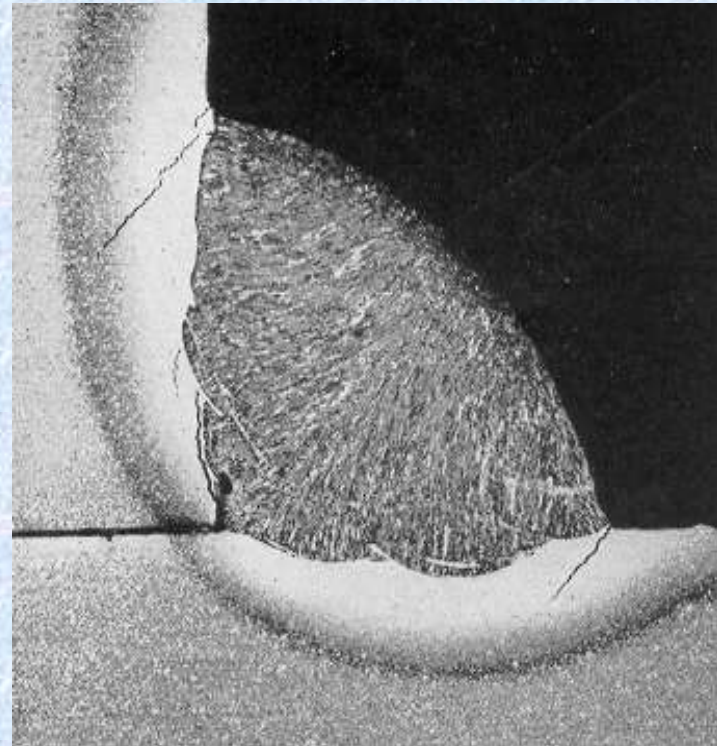
Hydrogen induced HAZ cracking

Hydrogen Induced Cold Cracking

Under bead cracking



Toe cracking

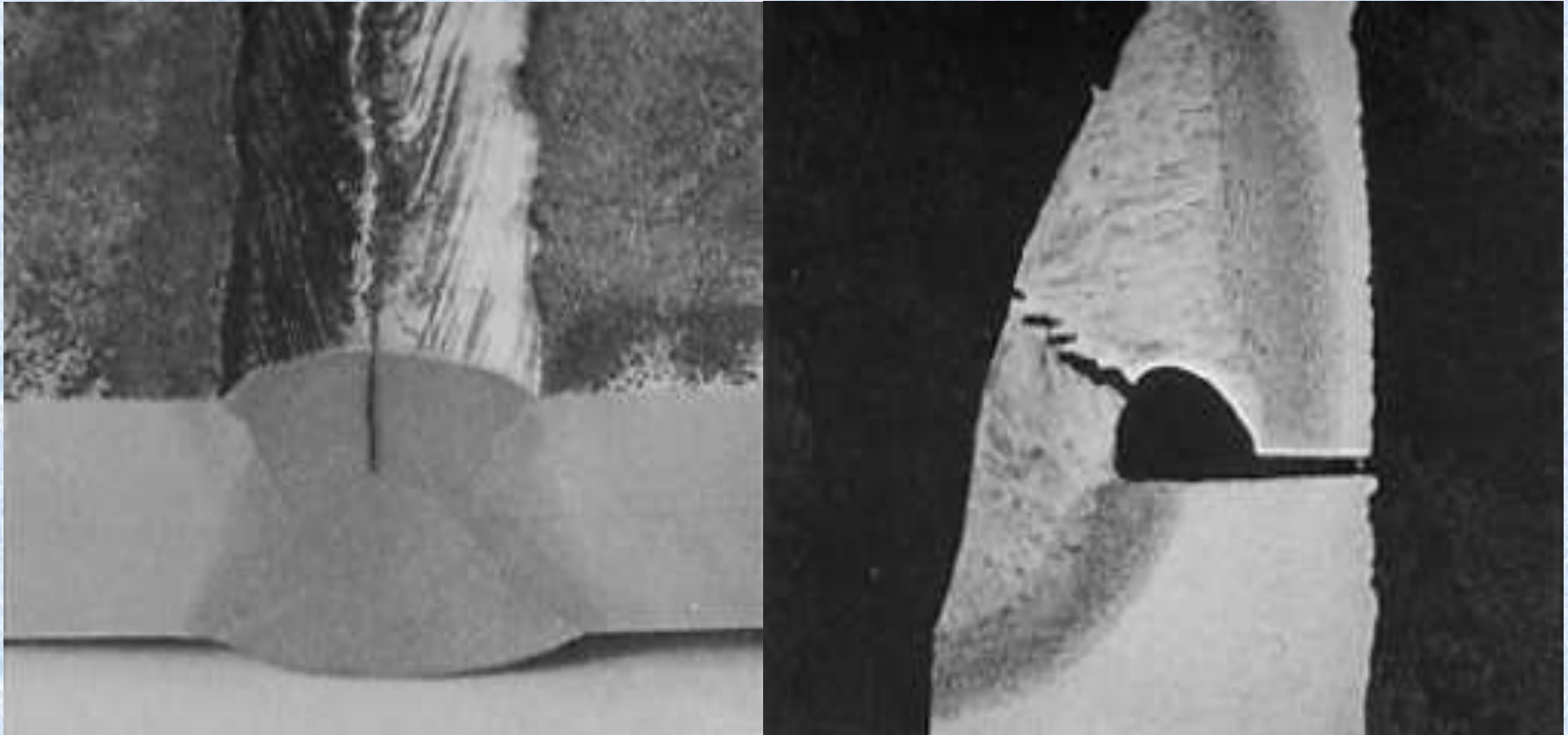


Hydrogen Cold Cracking Avoidance

To eliminate the risk of hydrogen cracking how do you remove the following:

- **Hydrogen**
 - MMA (basic electrodes). MAG
 - Cleaning weld prep etc.
- **Stress**
 - Design, Balanced welding.
- **Temperature**
 - Heat to 300°C (wrap & cool slowly)
- **Hardness**
 - Preheat-reduces cooling rate which reduces the risk of Susceptible Microstructure

Solidification Cracking



Usually Occurs in Weld Centerline

Solidification Cracking

Also referred as *Hot Cracking*

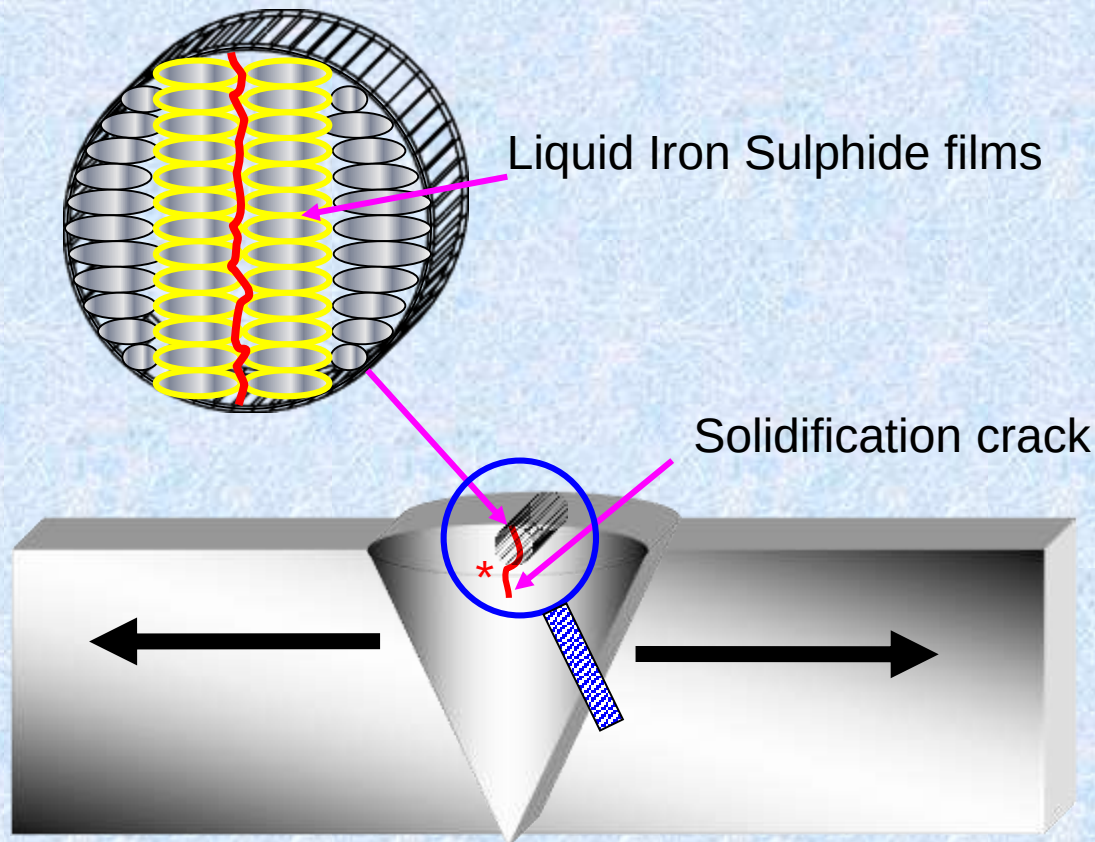
Crack type: Solidification cracking

Location: Weld centreline (longitudinal)

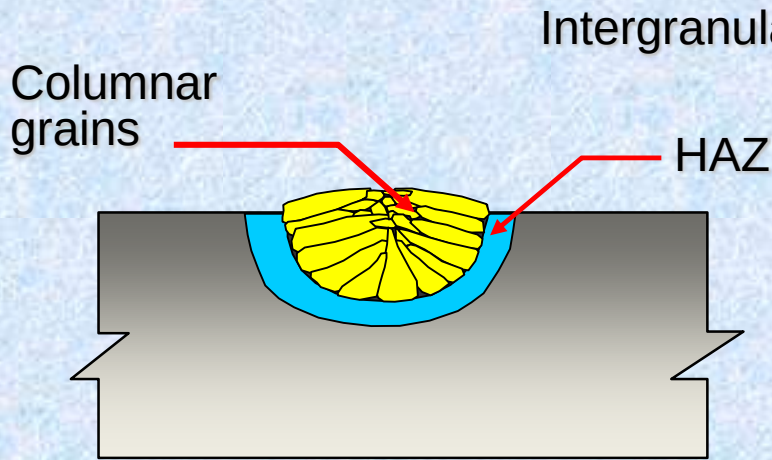
Steel types: High sulphur & phosphor
concentration in steels.

Susceptible Microstructure: Columnar grains In direction of
solidification

Solidification Cracking Fe Steels

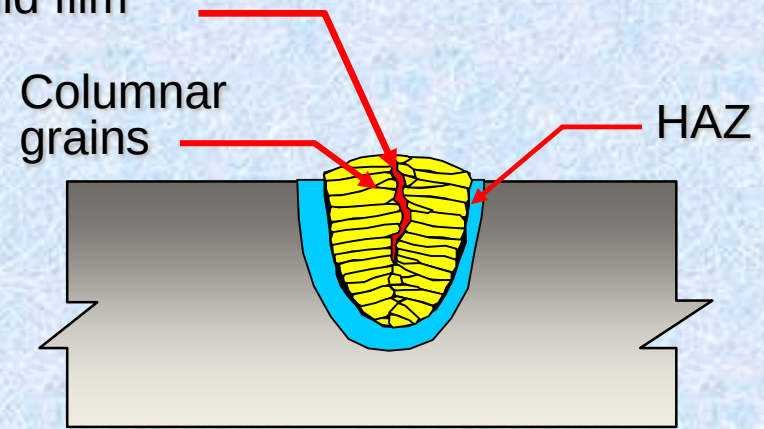


Solidification Cracking



Shallow, wider weld bead

On solidification the bonding between the grains may be adequate to maintain cohesion and a crack is unlikely to occur

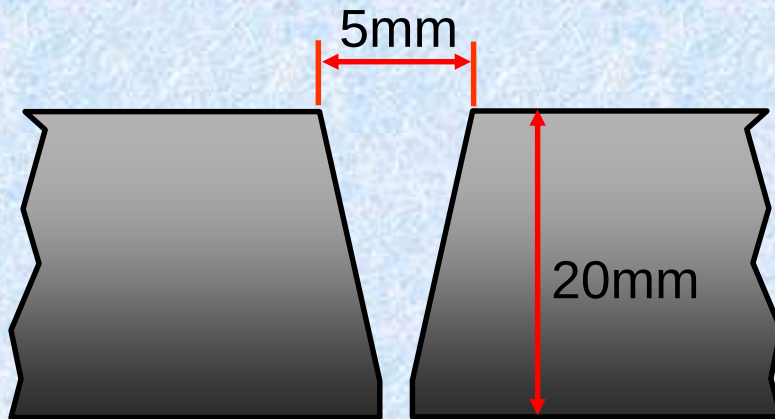


Deep, narrower weld bead

On solidification the bonding between the grains may now be very poor to maintain cohesion and a crack may result

Solidification Cracking

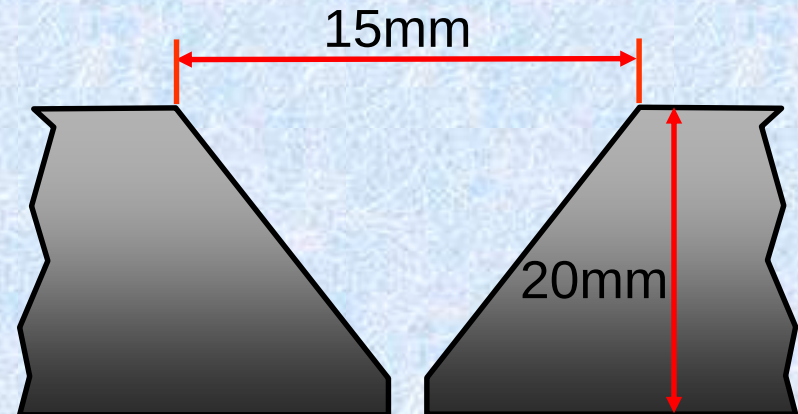
Depth to Width Ratios



$$\frac{\text{Width}}{\text{Depth}} = < 0.7 \quad \frac{5}{20} = 0.25$$

Cracking likely

Higher dilution levels
faster cooling



$$\frac{\text{Width}}{\text{Depth}} = > 0.7 \quad \frac{15}{20} = 0.75$$

Cracking unlikely

Lower dilution levels
slower cooling

Solidification Cracking

Precautions for controlling solidification cracking

- The first steps in eliminating this problem would be to choose a low dilution process, and change the joint design

Grind and seal in any lamination and avoid further dilution

Add Manganese to the electrode to form spherical Mn/S which form between the grain and maintain grain cohesion

As carbon increases the Mn/S ratio required increases exponentially and is a major factor. Carbon content % should be a minimised by careful control in electrode and dilution

Limit the heat input, hence low contraction, & minimise restraint

Lamellar Tearing

Crack type:

Lamellar
tearing

Location:

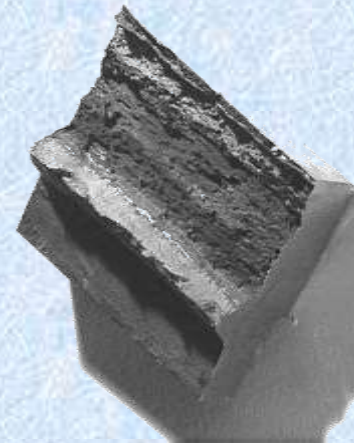
Below weld
HAZ

Steel types:

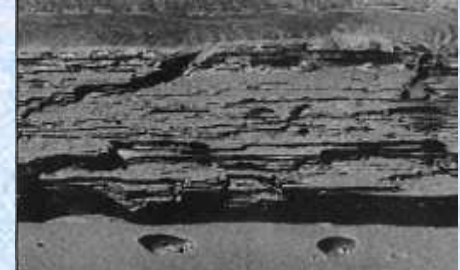
High sulphur
&
phosphorous
steels

Microstructure:

Lamination &
Segregation

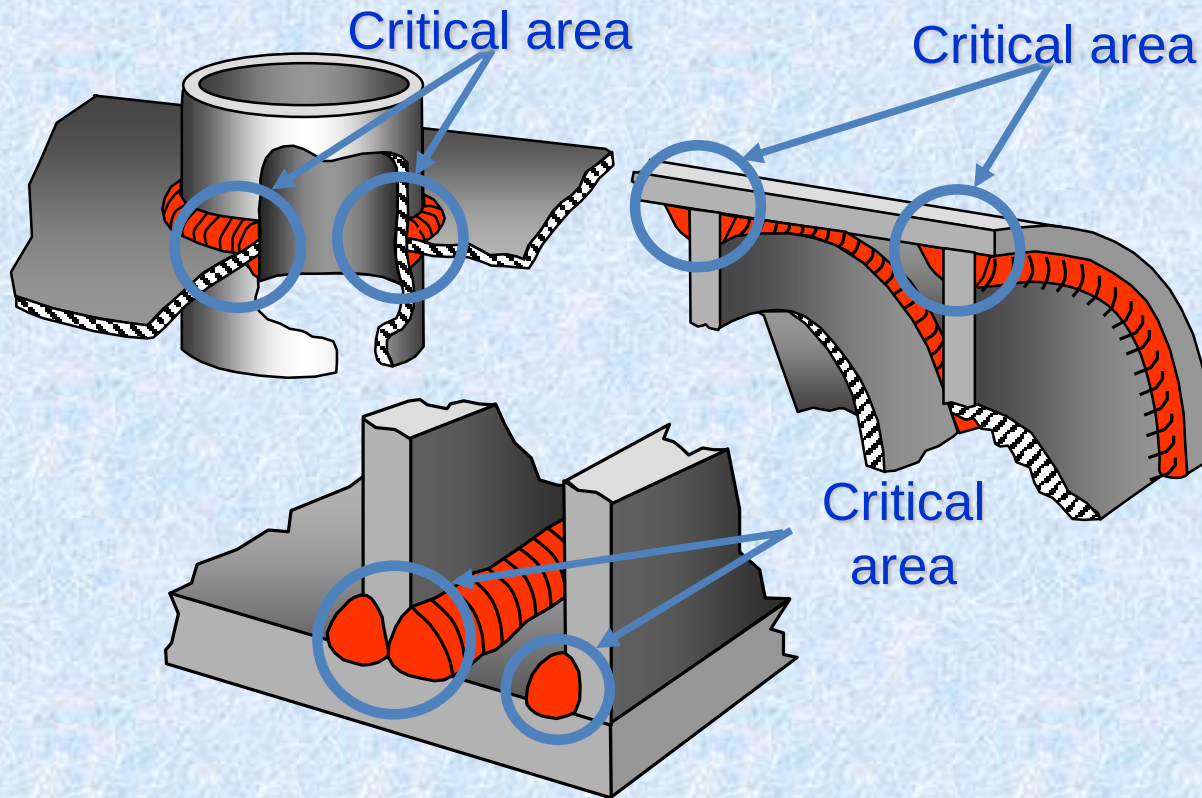


Step like appearance

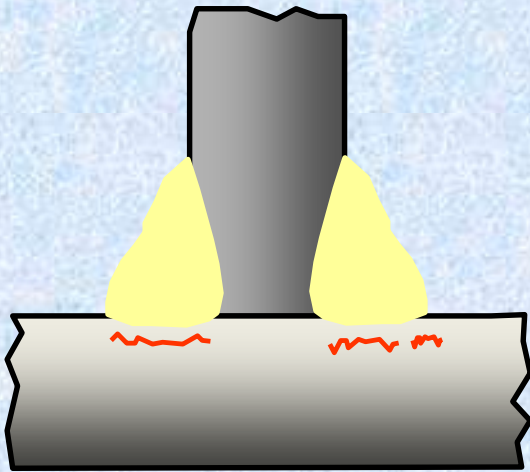


Cross section

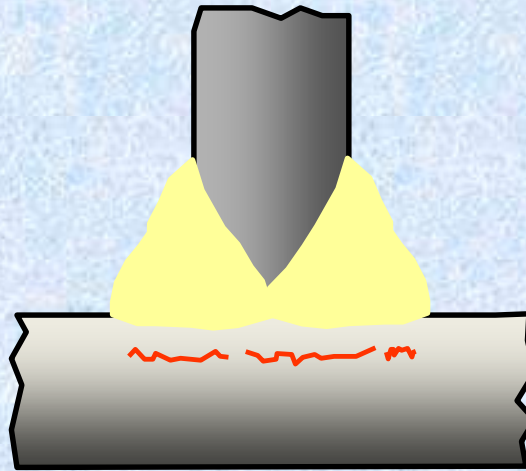
Lamellar Tearing



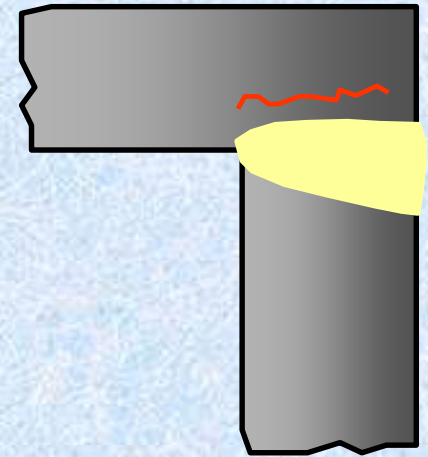
Lamellar Tearing



Tee fillet weld



Tee butt weld
(double-bevel)



Corner butt weld
(single-bevel)

Lamellar Tearing

Methods of avoiding Lamellar Tearing:*

- 1) Avoid restraint*
- 2) Use controlled low sulfur plate *
- 3) Grind out surface and butter *
- 4) Change joint design *
- 5) Use a forged T piece (Critical Applications)*

Intergranular Corrosion

Crack type: Inter-granular corrosion

Location: Weld HAZ. (longitudinal)

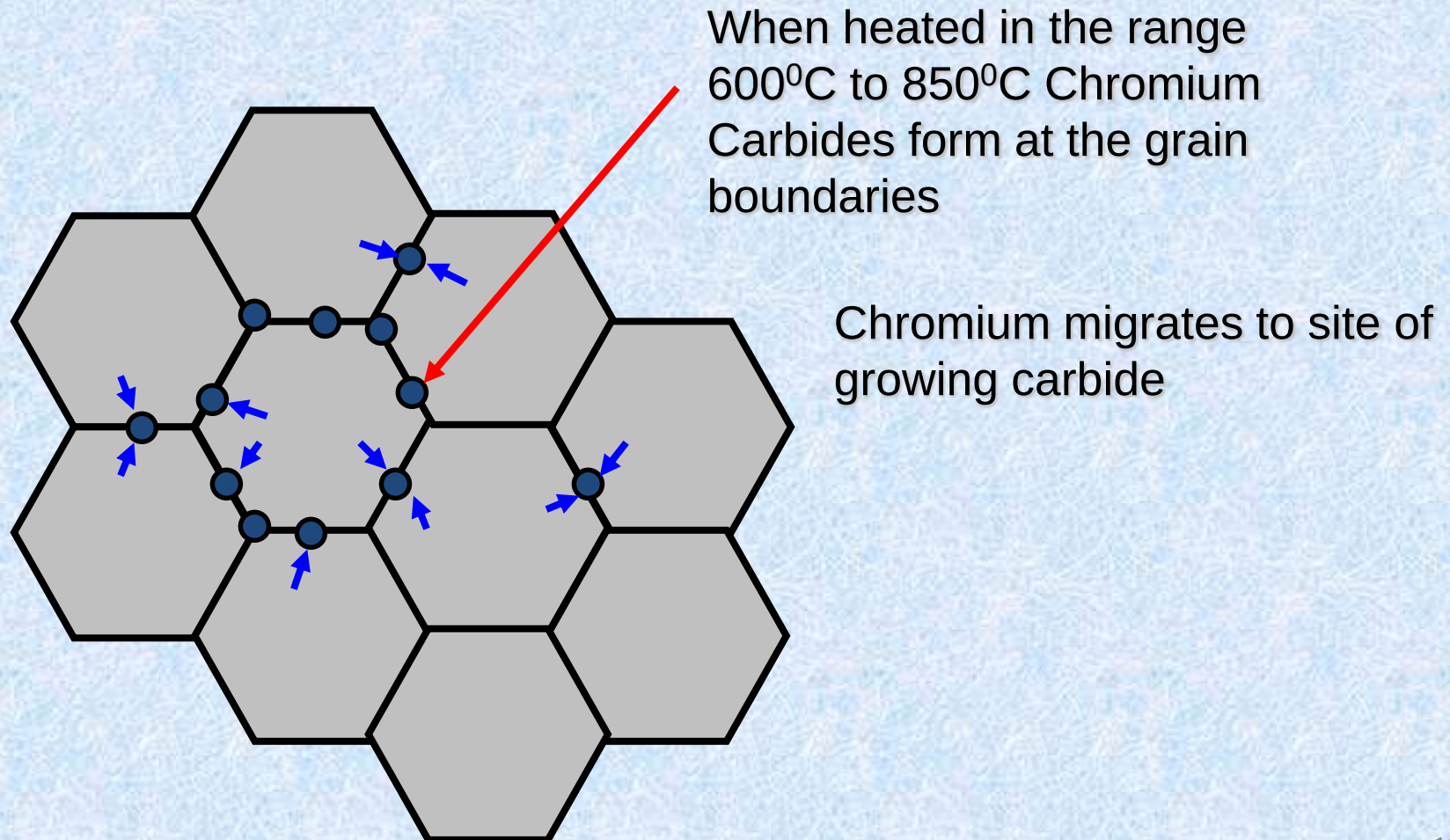
Steel types: Stainless steels

Microstructure: Sensitised grain boundaries

Occurs when:

An area in the HAZ has been sensitised by the formation of chromium carbides. This area is in the form of a line running parallel to and on both sides of the weld. This depletion of chromium will leave the effected grains low in chromium oxide which is what produces the corrosion resisting effect of stainless steels. If left untreated corrosion and failure will be rapid*

Inter-Granular Corrosion



Module – 8 : Destructive Testing and types of Destructive Testing

Destructive Testing

- In D.T, tests are carried out to the specimen's failure, in order to understand a specimen's structural performance or material behavior under different loads.
- These tests are generally much easier to carry out, yield more information, and are easier to interpret than NDT.
- Most suitable, and economic, for objects which will be mass-produced, as the cost of destroying a small number of specimens is negligible.
- It is usually not economical to do destructive testing where only one or very few items are to be produced (for example, in the case of a building)
- In DT, the failure can be accomplished using a sound detector or stress gauge.

Non-Destructive Testing

- NDT is a wide group of analysis techniques used in science and industry to evaluate the properties of a material, component or system without causing damage.
- It is a highly valuable technique that can save both money and time in product evaluation, troubleshooting, and research.
- Common NDT methods include ultrasonic, magnetic-particle, liquid penetrant, radiographic, remote visual inspection (RVI), eddy-current testing, and low coherence interferometry.
- NDT is commonly used in forensic engineering, mechanical engineering, electrical engineering, civil engineering, system engineering, aeronautical engineering and art.

Destructive testing

- Definition:

Mechanical properties of metals are related to the amount of deformation which metals can withstand under different circumstances of force application.

Malleability

Ductility

Toughness

Hardness

Tensile strength

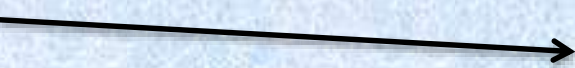


Ability of a material undergo plastic deformation under static tensile loading without rupture. Measurable elongation and reduction in cross section area.

Definition

Mechanical properties of metals are related to the amount of deformation which metals can withstand under different circumstances of force application.

- Malleability
- Ductility
- Toughness
- Hardness
- Tensile strength



Ability of a material to withstand bending or the application of shear stresses by impact loading without fracture.

Definition

Mechanical properties of metals are related to the amount of deformation which metals can withstand under different circumstances of force application.

- Malleability
- Ductility
- Toughness
- Hardness
- Tensile strength



Measurement of a material surface resistance to indentation from another material by static load.

Definition

Mechanical properties of metals are related to the amount of deformation which metals can withstand under different circumstances of force application.

- Malleability
- Ductility
- Toughness
- Hardness
- Tensile strength



Measurement of the maximum force required to fracture a materials bar of unit cross sectional area in tension

Types of Destructive testing

- Tensile test
- Bend test
- Impact Test

Tensile Testing

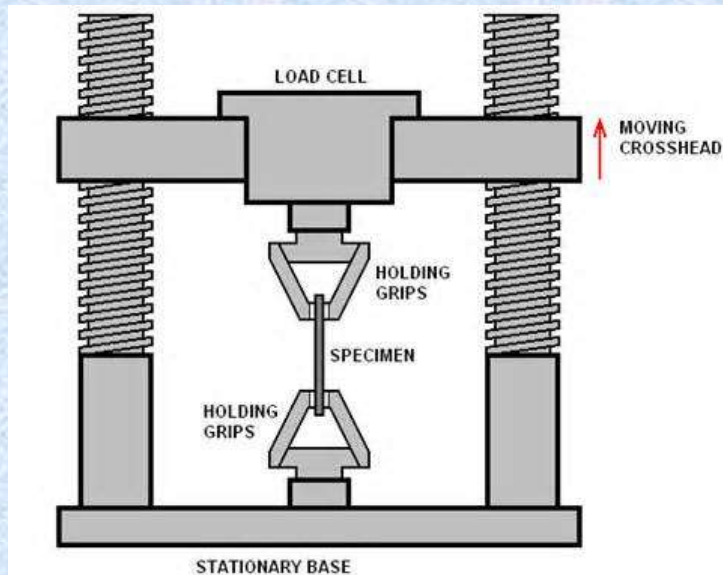
Properties determined by carrying out tensile test:

- Ultimate tensile strength (UTS)
- Yield strength (YS)/0.2% proof stress
- Percentage elongation (ductility)-E%
- Percentage reduction in area (RA)

Type of tensile test

- Reduce section transverse tensile (Flat/Round)
- All weld tensile test

Tensile Testing



Tensile Testing

- Formula:

$UTS = Load / Area$; $Area = Width * Thickness$

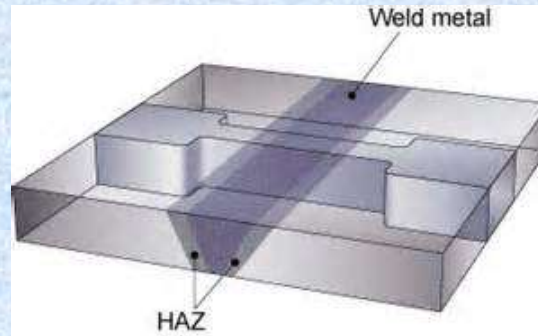
Example:

width=28 mm; Thickness = 10.0 mm

Area = 280 mm² ; Load = 165,000 N (Newtons)

$UTS = 165,000 / 280 = 589 \text{ N/mm}^2$

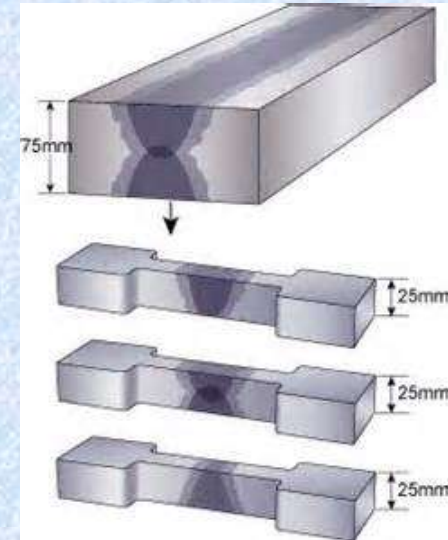
Transverse Tensile Test



Weld on Plate

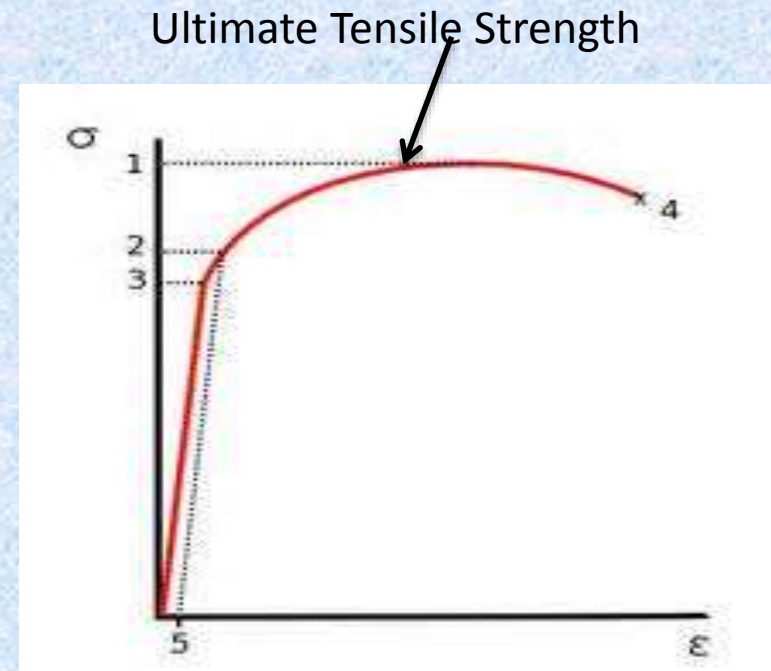
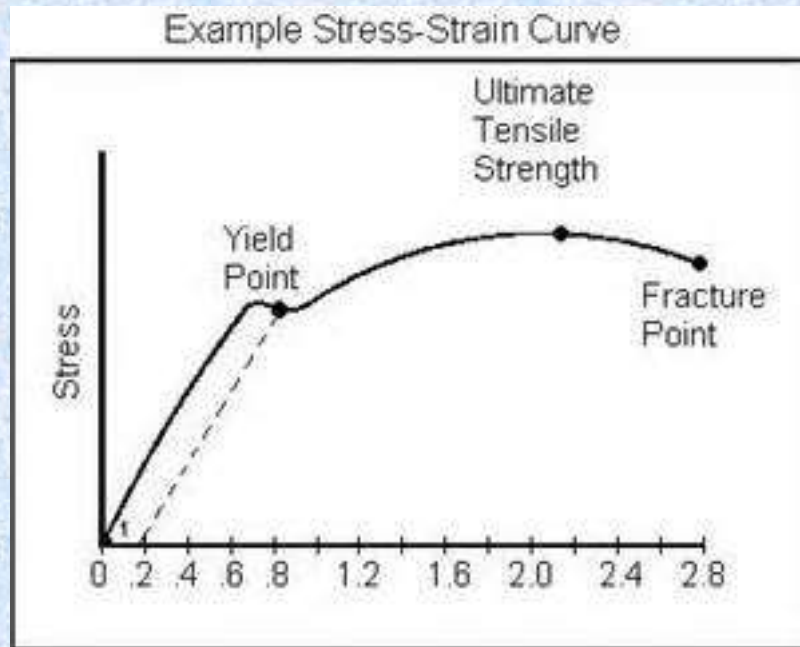


Weld on Pipe



Multiple cross joint specimen

Typical stress strain curve



Broken Sample of Transverse Tensile Test



Bend Test

This Test is designed to determine the metal soundness or its freedom from imperfections. Bend test are normally performed using some kind of bend jig. Most qualification test for mild steel require that specimen be bent around a mandrel having a diameter four times the thickness of specimen. This results in about 20% elongation on outer surface.

Type of bend test:

- Transverse bend Test (Root, face, Side)
- Longitudinal Bend Test (Root & Face)

The acceptability of bend test is normally judged based on size and/ or no. of defects which appear on the tension surface

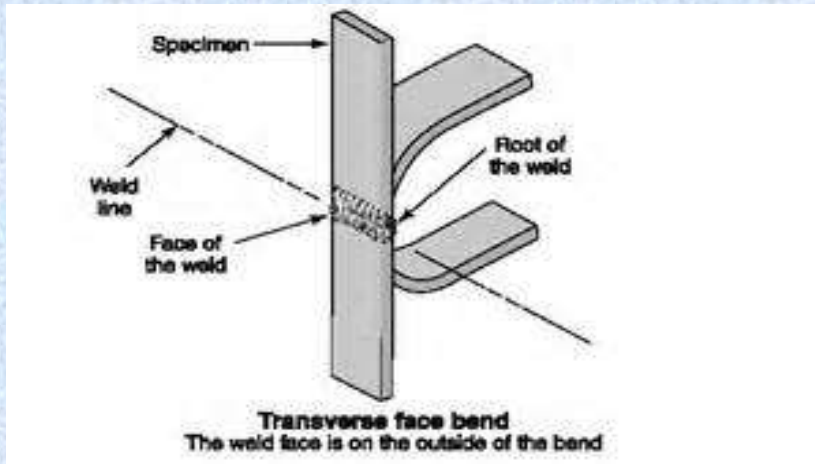
Bend Test

Objective of Test:

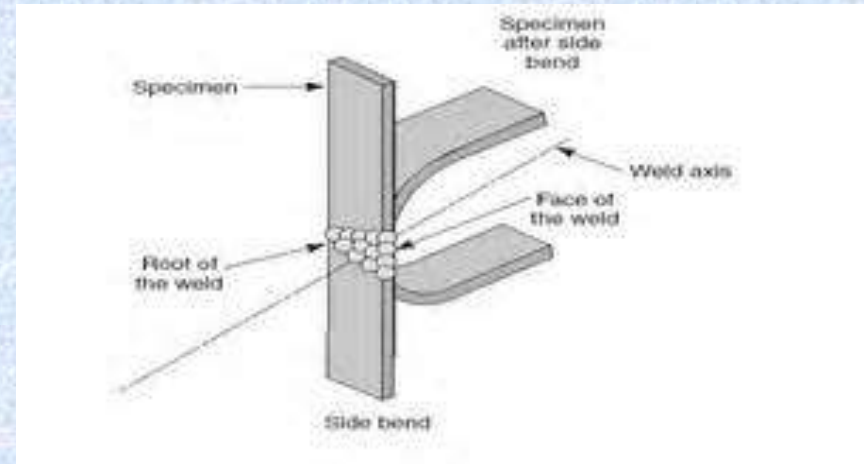
To determine the soundness of the weld zone. Bend testing can also be used to give an assessment of weld zone ductility.

- There are three ways to perform a bend test:
- Root Bend
- Face Bend
- Side Bend

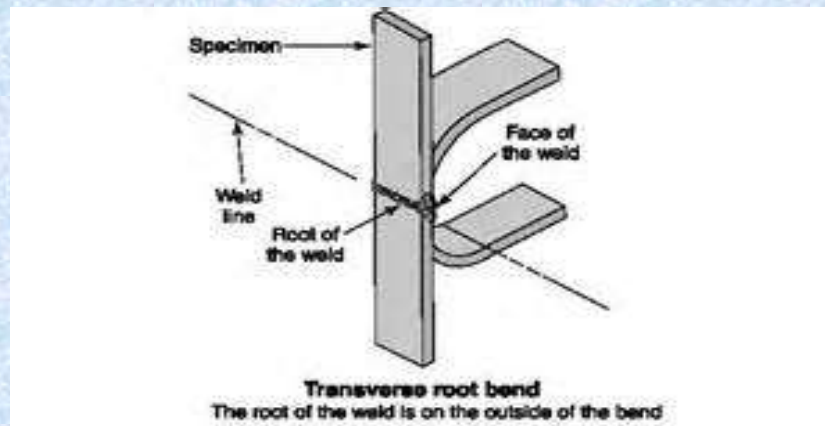
Bend Test



Face Bend



Side Bend



Root Bend

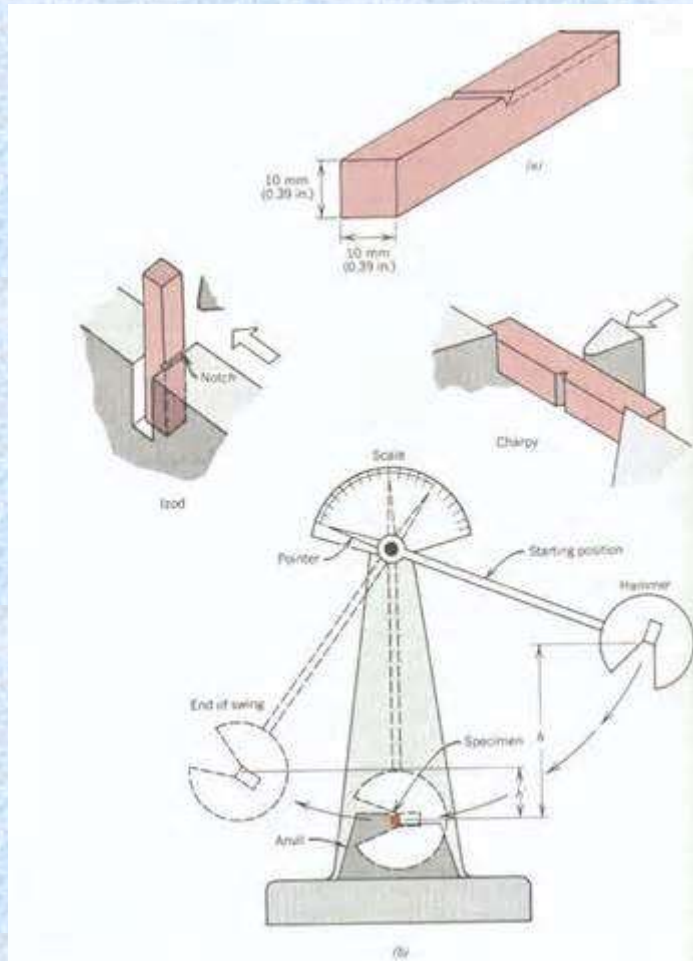
Charpy V-Notch Impact test Specimen



Charpy Impact Test

- The **Charpy impact test**, also known as the Charpy V-notch test, is a standardized high strain-rate test which determines the amount of energy absorbed by a material during fracture.
- This absorbed energy is a measure of a given material's toughness and acts as a tool to study temperature-dependent ductile-brittle transition.
- It is widely applied in industry, since it is easy to prepare and conduct and results can be obtained quickly and cheaply.
- Impact Testing is done in low temp. or at room temp. to know the impact.
- ❖ Standard size of metal for test specimen is 10mm.

Charpy Impact Test



Comparison Charpy Impact Test

Room Temp.

- 197 Joules
- 191 Joules
- 186 Joules

Avg. = 191 Joules

-20°C Temp.

- 49 Joules
- 53 Joules
- 51 Joules

Avg. = 51 Joules

The Test result shows that the specimen carried out at room Temp. absorb more energy than the specimen carried out at -20°C .

Hardness Testing

Definition:

- Measurement of resistance of a material against penetration of an indenter under a constant load.
- There is a direct correlation between UTS and hardness.

Hardness Test:

- Brinell
- Vickers
- Rockwell

Hardness Testing

Objectives:

- Measuring hardness in different areas of a welded joint
- Assessing resistance toward brittle fracture, cold cracking and corrosion sensitivity within a H₂S (Hydrogen Sulphide)

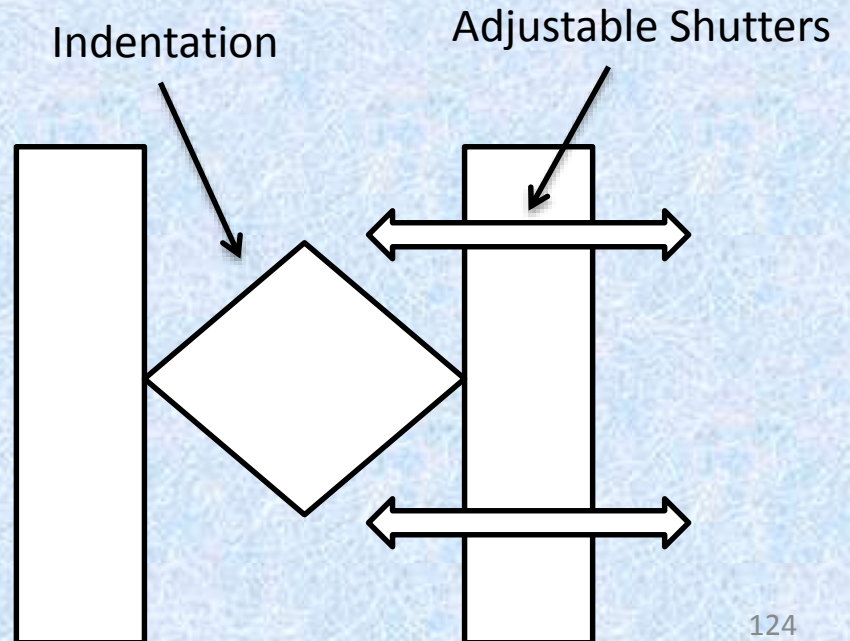
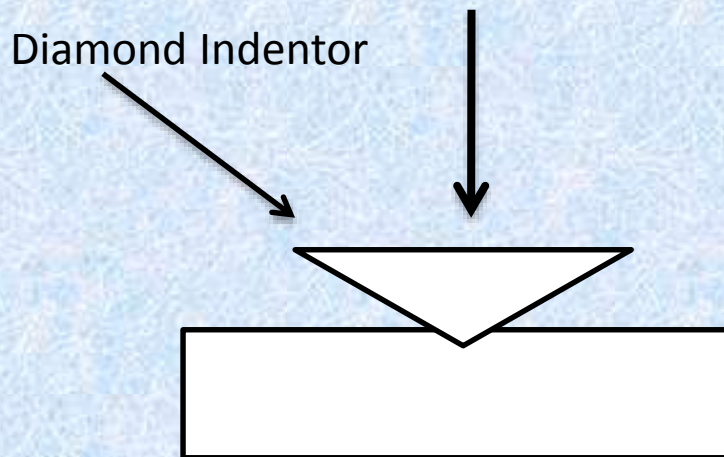
Information to be supplied on the test report:

- Material type
- Location of indentation
- Type of hardness test and load applied on the indenter
- Hardness value

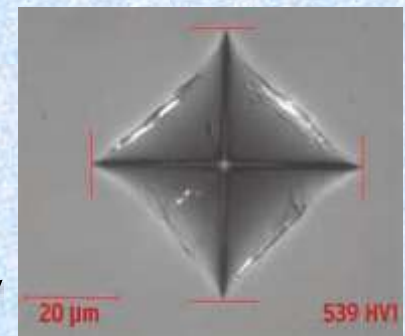
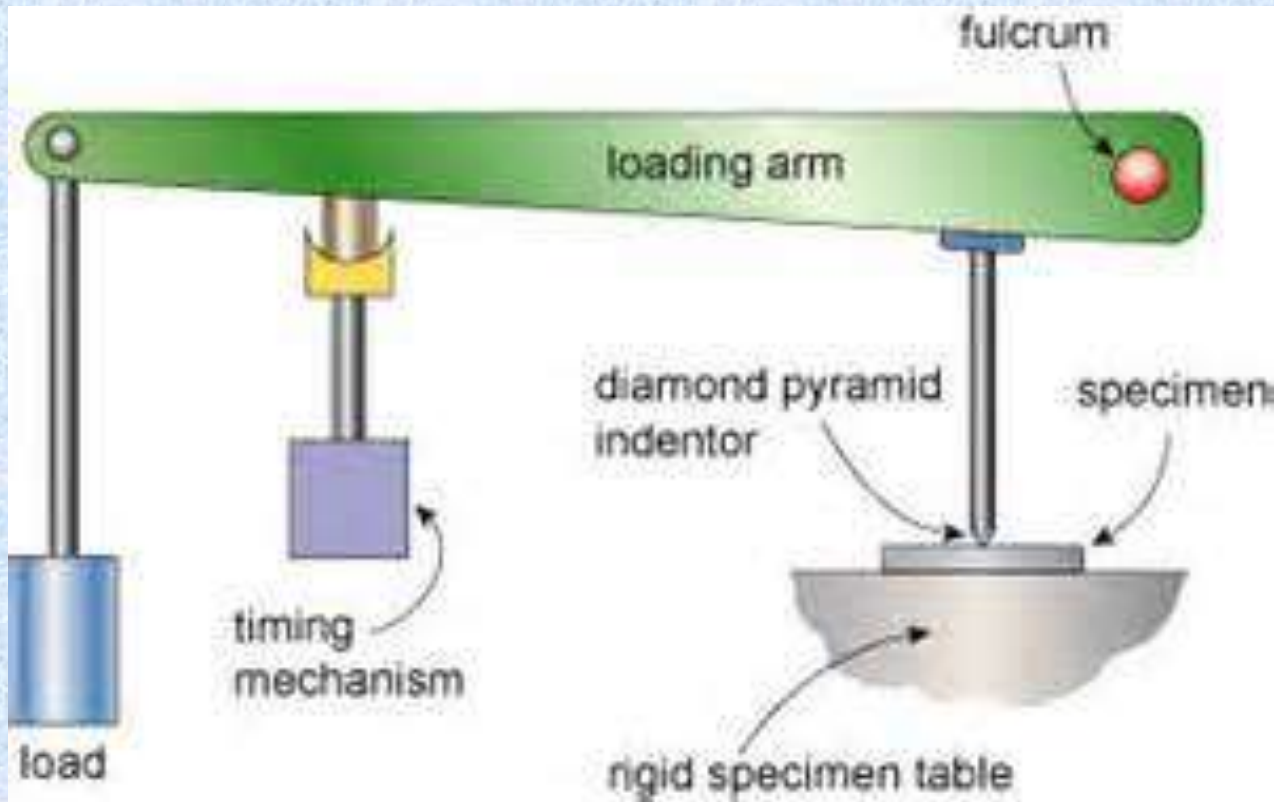
Vickers Hardness Test

Vickers Hardness tests:

- Indentation body is a square based diamond pyramid (136° included angle)
- The average diagonal (d) of the impression is converted to a hardness number from a table
- It is measured in HV₅, HV₁₀ or HV₀₂₅



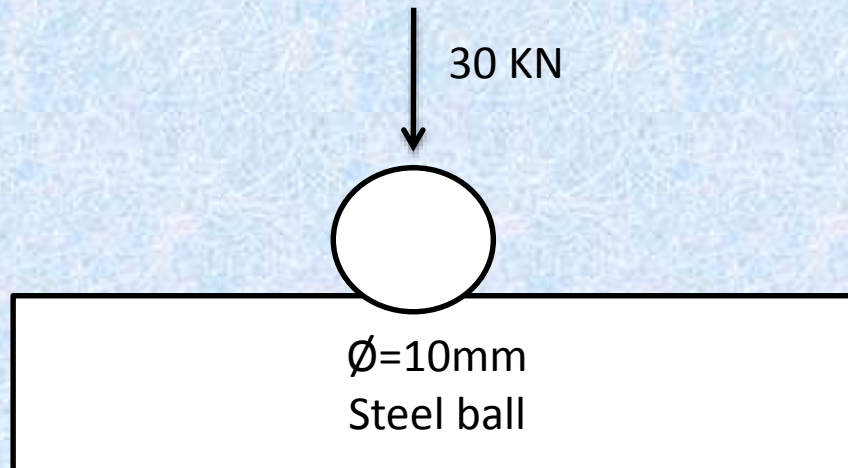
Vickers Hardness Test Machine



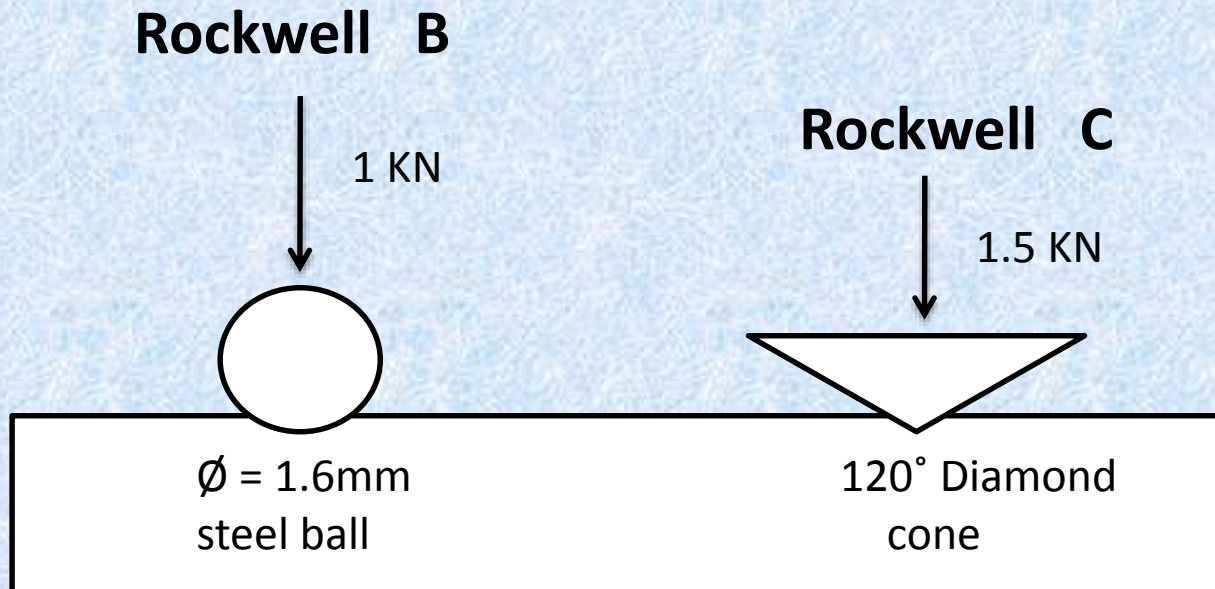
Impression

Brinell Hardness Test

- Hardened steel ball of given diameter is subjected for a given time to a given load.
- Load divided by area of indentation gives Brinell hardness in kg/mm^2
- More suitable for on site hardness testing



Rockwell Hardness Test

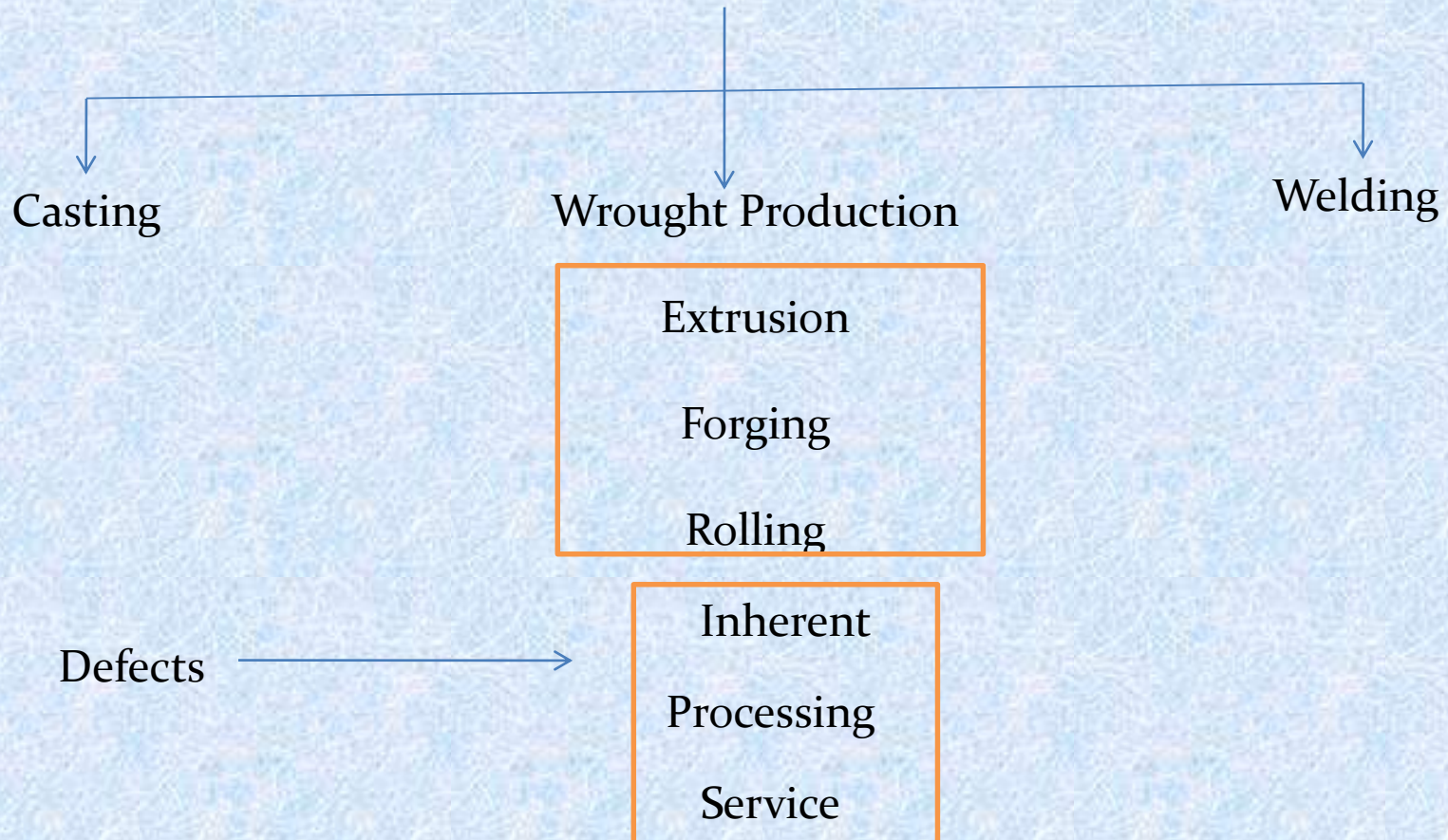


Which test is done to avoid brittleness of metal and at what temp. it is done?

Module – 9 : Forging, Casting, Rolling

Product Technology

Steel Product



Heat Treatment

Casting

- Casting involves pouring liquid metal into a mold, which contains a hollow cavity of the desired shape and then allowing it to cool and solidify.
- Solidified part is known as a casting, which is ejected or broken out of the mold to complete the process.
- Casting process have been known for thousands of years and widely used for sculpture, especially in bronze, jewellery in precious metals, weapons and tools
- Traditional techniques include lost-wax casting, plaster mold casting and sand casting.

Casting

Expendable Casting

- Sand casting
- Plaster Mold Casting
- Shell Molding
- Investment Casting
- Waste Molding of plaster
- Evaporative pattern Casting

Non-Expendable casting

- Permanent Mold Casting
- Die Casting
- Semi solid metal casting
- Centrifugal Casting
- Continuous Casting

Expendable Mold Casting

Sand Casting:

- Sand casting, also known as sand molded casting, is a metal casting process characterized by using sand as the mold material.
- Sand casting is relatively cheap and sufficiently refractory even for steel foundry use.
- In addition to the sand, a suitable bonding agent (usually clay) is mixed or occurs with the sand. The mixture is moistened, typically with water, but sometimes with other substances, to develop strength and plasticity of the clay and to make the aggregate suitable for molding.
- The sand is typically contained in a system of frames or mold boxes known as a flask.

Plaster mold casting

- Plaster casting is similar to sand casting except that Plaster of Paris is substituted for sand as a mold material.
- Generally, the form takes less than a week to prepare, after which a production rate of 1–10 units/hr mold is achieved, with items as massive as 45 kg (99 lb) and as small as 30 g (1 oz) with very good surface finish and close tolerances.
- Plaster casting is an inexpensive alternative to other molding processes for complex parts due to the low cost of the plaster and its ability to produce near net shape castings.

Shell Molding

- Shell molding is similar to sand casting, but the molding cavity is formed by a hardened "shell" of sand instead of a flask filled with sand.
- The sand used is finer than sand casting sand and is mixed with a resin so that it can be heated by the pattern and hardened into a shell around the pattern.
- Because of the resin and finer sand, it gives a much finer surface finish.
- Common metals that are cast include cast iron, aluminum, magnesium, and copper alloys.
- This process is ideal for complex items that are small to medium sized.

Investment Casting

- Investment casting (known as lost- wax casting in art) is a process that has been practiced for thousands of years, with the lost-wax process being one of the oldest known metal forming techniques.
- Investment casting derives its name from the fact that the pattern is invested, or surrounded, with a refractory material.
- The wax patterns require extreme care for they are not strong enough to withstand forces encountered during the mold making.
- One advantage of investment casting is that the wax can be reused.
- generally used for small castings, this process has been used to produce complete aircraft door frames, with steel castings of up to 300 kg and aluminum castings of up to 30 kg.

Waste molding of plaster

- In waste molding a simple and thin plaster mold, reinforced by sisal or burlap, is cast over the original clay mixture.
- When cured, it is then removed from the damp clay, incidentally destroying the fine details in undercuts present in the clay, but which are now captured in the mold.
- The mold may then at any later time (but only once) be used to cast a plaster positive image, identical to the original clay.
- The surface of this plaster may be further refined and may be painted and waxed to resemble a finished bronze casting.

Evaporative-pattern casting

- This is a class of casting processes that use pattern materials that evaporate during the pour, which means there is no need to remove the pattern material from the mold before casting.
- The two main processes are **lost-foam casting** and **full-mold casting**.
- **Lost-foam casting:** Lost-foam casting is a type of evaporative-pattern casting process that is similar to investment casting except foam is used for the pattern instead of wax.
- **Full-mold casting:** Full-mold casting is an evaporative-pattern casting process which is a combination of sand casting and lost-foam casting. It uses an expanded polystyrene foam pattern which is then surrounded by sand, much like sand casting. The metal is then poured directly into the mold, which vaporizes the foam upon contact.

Non-Expendable Mold Casting

Permanent mold casting:

- Permanent mold casting is a metal casting process that employs reusable molds ("permanent molds"), usually made from metal.
- The most common process uses gravity to fill the mold, however gas pressure or a vacuum are also used.
- A variation on the typical gravity casting process, called slush casting, produces hollow castings.
- Common casting metals are aluminum, magnesium, and copper alloys. Other materials include tin, zinc, and lead alloys and iron and steel are also cast in graphite molds.
- Permanent molds, while lasting more than one casting still have a limited life before wearing out.

Die casting

- The die casting process forces molten metal under high pressure into mold cavities (which are machined into dies).
- Most die castings are made from non-ferrous metals, specifically zinc, copper, and aluminum based alloys, but ferrous metal die castings are possible.
- The die casting method is especially suited for applications where many small to medium sized parts are needed with good detail, a fine surface quality and dimensional consistency.

Semi-solid metal casting

- Semi-solid metal (SSM) casting is a modified die casting process that reduces or eliminates the residual porosity present in most die castings
- Rather than using liquid metal as the feed material, SSM casting uses a higher viscosity feed material that is partially solid and partially liquid.
- A modified die casting machine is used to inject the semi-solid slurry into re-usable hardened steel dies
- The high viscosity of the semi-solid metal, along with the use of controlled die filling conditions, ensures that the semi-solid metal fills the die in a non-turbulent manner so that harmful porosity can be essentially eliminated.

Centrifugal casting

- In this process molten metal is poured in the mold and allowed to solidify while the mold is rotating
- Metal is poured into the center of the mold at its axis of rotation. Due to centrifugal force the liquid metal is thrown out towards the periphery.
- Centrifugal casting is both gravity- and pressure-independent since it creates its own force feed using a temporary sand mold held in a spinning chamber at up to 900 N.

Continuous casting

- Continuous casting is a refinement of the casting process for the continuous, high-volume production of metal sections with a constant cross-section.
- Molten metal is poured into an open-ended, water-cooled mold, which allows a 'skin' of solid metal to form over the still-liquid centre, gradually solidifying the metal from the outside in.
- After solidification, the strand, as it is sometimes called, is continuously withdrawn from the mold.
- Metals such as steel, copper, aluminum and lead are continuously cast, with steel being the metal with the greatest tonnages cast using this method.

At which temp. forging is performed?

Module – 10: Weldability of Steels

Weldability of Steels

Meaning:

It relates to the ability of the metal (or alloy) to be welded with mechanical soundness by most of the common welding processes, and the resulting welded joint retain the properties for which it has been designed.

It is a function of many inter-related factors but these may be summarised as:

- Composition of parent material
- Joint design and size
- Process and technique
- Access

Weldability of Steels

The weldability of steel is mainly dependant on carbon & other alloying elements content.

If a material has limited weldability, we need to take special measures to ensure the maintenance of the properties required

Poor weldability normally results in the occurrence of cracking

A steel is considered to have poor weldability when:

- an acceptable joint can only be made by using very narrow range of welding conditions
- great precautions to avoid cracking are essential (*e.g., high pre-heat etc*)

The Effect of Alloying on Steels

Elements may be added to steels to produce the properties required to make it useful for an application.

Most elements can have many effects on the properties of steels.

Other factors which affect material properties are:

- The temperature reached before and during welding
- Heat input
- The cooling rate after welding and or PWHT.

Classification of Steels

Types of Weldable:

C, C-Mn & Low Alloy Steels

Carbon Steels

- Carbon contents up to about $\sim 0.25\%$
- Manganese up to $\sim 0.8\%$
- Low strength and moderate toughness

Carbon-Manganese Steels

- Manganese up to $\sim 1.6\%$
- Carbon steels with improved toughness due to additions of Manganese

Classification of Steels

Mild steel ($CE < 0.4$)

- Readily weldable, preheat generally not required if low hydrogen processes or electrodes are used
- Preheat may be required when welding thick section material, high restraint and with higher levels of hydrogen being generated

C-Mn, medium carbon, low alloy steels (CE 0.4 to 0.5)

- Thin sections can be welded without preheat but thicker sections will require low preheat levels and low hydrogen processes or electrodes should be used

Higher carbon and alloyed steels ($CE > 0.5$)

- Preheat, low hydrogen processes or electrodes, post weld heating and slow cooling may be required

Carbon equivalent Formula

The weldability of the material will also be affected by the amount of alloying elements present.

The Carbon Equivalent of a given material also depends on its alloying elements

- The higher the *CE*, higher the susceptibility to brittleness, and lower the weldability
- The *CE* or CEV is calculated using the following formula:

The weldability of the material will also be affected by the amount of alloying elements present.

The Carbon Equivalent of a given material also depends on its alloying elements

- The higher the *CE*, higher the susceptibility to brittleness, and lower the weldability
- The *CE* or CEV is calculated using the following formula:

$$CEV = \%C + \frac{Mn\%}{6} + \frac{Cr\%}{5} + \frac{Mo\%}{6} + \frac{V\%}{15} + \frac{Cu\%}{15} + \frac{Ni\%}{15}$$

Low-Alloy Chromium Steels

- Steel included in this group are the AISI type 5015 to 5160 and the electric furnace steels 50100, 51100, and 52100.
- In these steels carbon ranges from 0.12-1.10%, manganese from 0.30-1.00%, chromium from 0.20-1.60%, and silicon from 0.20-0.30%.
- When carbon is at low end of the range, these steels can be welded without special precautions.
- As the carbon increases and as the chromium increases, high hardenability results and a preheat of as high 400°C will be required, particularly for heavy sections.

Low-Alloy Chromium Steels

- When using the submerged arc welding process, it is also necessary to match the composition of the electrode with the composition of the base metal.
- A flux that neither detracts nor adds elements to the weld metal should be used.
- In general, preheat can be reduced for submerged arc welding because of the higher heat input and slower cooling rates involved.
- To make sure that the submerged arc deposit is low hydrogen, the flux must be dry and the electrode and base metal must be clean.

Low-Alloy Chromium Steels

- When using the gas metal arc welding process, the electrode should be selected to match the base metal and the shielding gas should be selected to avoid excessive oxidation of the weld metal.
- Preheating with the gas metal arc welding (GMAW) process should be in the same order as with shielded metal arc welding (SMAW) since the heat input is similar.

Module – 11 : Fundamentals of High Alloy Steel

Alloy Steels

- Alloy steel is any type of steel to which one or more elements besides carbon have been intentionally added, to produce a desired physical property or characteristic.
- Common elements that are added to make alloy steel are molybdenum, manganese, nickel, silicon, boron, chromium, and [vanadium](#).
- **Alloy steel** is steel that is alloyed with a variety of elements in total amounts between 1.0% and 50% by weight to improve its mechanical properties.

Low Alloy Steel

- Low alloy steels, typically plain carbon steels that have only two-alloys elements but can be as high as five-alloying elements.
- The majority of the alloying is less than 2% and in most cases under 1%.
- Nickel (Ni) can be as high as 5%, but this is an exception and may be found in transmission gearing.
- In the chemical analysis you will find many more elements but these are incidental to the making of the steel as opposed to alloying to for specific property in the steel of normally less than 2%.

High Alloy Steel

- High Alloy Steel is a type of alloy steel that provides better mechanical properties or greater resistance to corrosion than carbon steel.
- High Alloy steels vary from other steels in that they are not made to meet a specific chemical composition but rather to specific mechanical properties.
- They have a carbon content between 0.05–0.25% to retain formability and weldability.

Advantages of High Alloy Steel

- They are used in cars, trucks, cranes, bridges, roller coasters and other structures that are designed to handle large amounts of stress or need a good strength-to-weight ratio.
- High Alloy steel cross-sections and structures are usually 20 to 30% lighter than a carbon steel with the same strength.
- High Alloy Steels are also more resistant to rust than most carbon steels because of their lack of Pearlite – the fine layers of ferrite (almost pure iron) and Cementite in Pearlite.
- High Alloy Steels usually have densities of around 7800 kg/m^3 .

High Alloy Steel Classes

- **Stainless Steels** (Corrosion Resistance) for stress corrosion cracking (SCC).

High Temperature Steels (+)1000F: These are steels that must have good resistance to high-temperature creep and ruptures. Also important to be resistive to oxidation and corrosion. Stainless steels also fit this class except ferritic.

Low Temperature Steels (-)300F: This class of application is suited best for stainless steels of the austenitic type. Low carbon high alloy steel do not perform well at -40F unless steps are taken to alter the steel characteristics, and regardless of purity and chemical character (-) 300F is where performance is unacceptable. Austenitic type is very suited for this -300F temperature with alloying.

High Alloy Steel Classes

- **Wear Resistance Steels** - These are done by diffusing gases like carburizing, sulfiding, siliconizing, nitriding, and boriding to mention a most methods. Other methods are through alloying and coating the high alloy steels.
- **Electro-magnetic Steels** - These are transformer and generator plain carbon steels including iron cores. Permanent magnetic also fit this class. Silicon (Si) is an important alloy.

High Alloy Steel Classes

- Tooling Steel - These are cutting tools, forming dies, and shearing tools; they can be hardened and will have a high carbon content.
- Tools like chisels can have carbon (C) content up to 1.10% and razor blades has high as 1.40% C.
- Tools will have different chemical composition for low speed tooling (including pneumatic powered) and high speed tools where abrasion is important.

Classification of High Alloy Steel

- **Weathering Steels:** steels which have better corrosion resistance. A common example is COR-TEN.
- **Control-rolled steels:** hot rolled steels which have a highly deformed austenite structure that will transform to a very fine equiaxed ferrite structure upon cooling.
- **Pearlite-reduced steels:** low carbon content steels which lead to little or no pearlite, but rather a very fine grain ferrite matrix. It is strengthened by precipitation hardening.

Classification of High Alloy Steel

- **Acicular Ferrite Steel:** These steels are characterized by a very fine high strength acicular ferrite structure, a very low carbon content, and good hardenability.
- **Dual Phase Steel:** These steels have a ferrite microstructure that contain small, uniformly distributed sections of Martensite. This microstructure gives the steels a low yield strength, high rate of work hardening, and good formability.
- **Micro-alloyed Steel:** steels which contain very small additions of niobium, vanadium, and/or titanium to obtain a refined grain size and/or precipitation hardening.

SAE High Alloy steel grade compositions

The Society of Automotive Engineers (SAE) maintains standards for High Alloy steel grades because they are often used in automotive applications.

Grade	% Carbon (max)	% Manganese (max)	% Phosphorus (max)	% Sulfur (max)	% Silicon (max)	Notes
942X	0.21	1.35	0.04	0.05	0.90	Niobium or vanadium treated
945A	0.15	1.00	0.04	0.05	0.90	
945C	0.23	1.40	0.04	0.05	0.90	
945X	0.22	1.35	0.04	0.05	0.90	Niobium or vanadium treated
950A	0.15	1.30	0.04	0.05	0.90	
950B	0.22	1.30	0.04	0.05	0.90	
950C	0.25	1.60	0.04	0.05	0.90	
950D	0.15	1.00	0.15	0.05	0.90	
950X	0.23	1.35	0.04	0.05	0.90	Niobium or vanadium treated

SAE High Alloy steel grade compositions

Grade	% Carbon (max)	% Manganese (max)	% Phosphorus (max)	% Sulfur (max)	% Silicon (max)	Notes
955X	0.25	1.35	0.04	0.05	0.90	Niobium, vanadium, or nitrogen treated
960X	0.26	1.45	0.04	0.05	0.90	Niobium, vanadium, or nitrogen treated
965X	0.26	1.45	0.04	0.05	0.90	Niobium, vanadium, or nitrogen treated
970X	0.26	1.65	0.04	0.05	0.90	Niobium, vanadium, or nitrogen treated
980X	0.26	1.65	0.04	0.05	0.90	Niobium, vanadium, or nitrogen treated

Ranking of various properties for SAE High Alloy steel grades

Rank	Weldability	Formability	Toughness
Worst	980X	980X	980X
	970X	970X	970X
	965X	965X	965X
	960X	960X	960X
	955X, 950C, 942X	955X	955X
	945C	950C	945C, 950C, 942X
	950B, 950X	950D	945X, 950X
	945X	950B, 950X, 942X	950D
	950D	945C, 945X	950B
	950A	950A	950A
Best	945A	945A	945A

What is the percentage of carbon content in High alloy steels and why it is used?

Module – 12 : Solidification of Metals and Alloys

Solidification of Metal

- Solidification is the process of transformation from a liquid phase to a solid phase.
- It requires heat removal from the system. metals have a melting point (well defined temperature) above which liquid is stable and below that solid is stable.
- Solidification is a very important process as it is most widely used for shaping of materials to desired product.

Solidification of Metal & Alloys

- Solidification of a metal can be divided into the following steps:
- Formation of a stable nucleus
- Growth of a stable nucleus
- Growth of Crystals

Cooling Curves

- **Undercooling** - The temperature to which the liquid metal must cool below the equilibrium freezing temperature before nucleation occurs.
- **Recalescence** - The increase in temperature of an under cooled liquid metal as a result of the liberation of heat during nucleation.
- **Thermal arrest** - A plateau on the cooling curve during the solidification of a material caused by the evolution of the latent heat of fusion during solidification.
- **Total solidification time** - The time required for the casting to solidify completely after the casting has been poured.
- **Local solidification time** - The time required for a particular location in a casting to solidify once nucleation has begun.

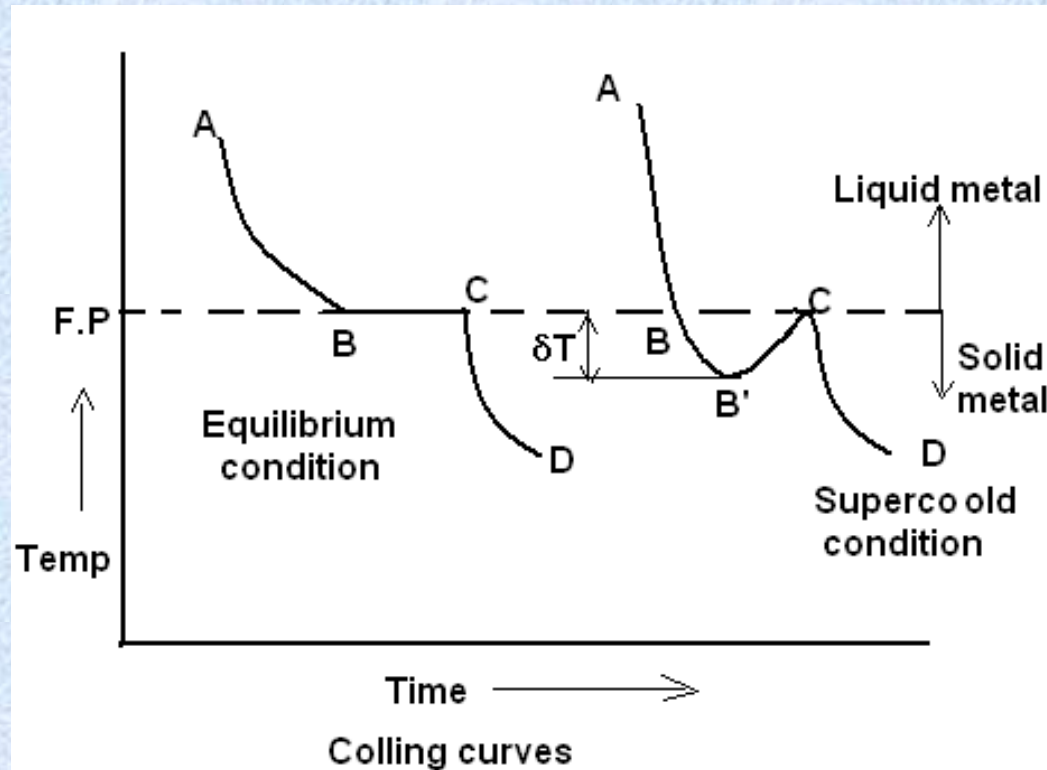
Solidification of pure metals:

- Temperature remains constant while grains grow.
- Some metals undergo allotropic transformation in solid state. For example on cooling bcc δ -iron changes to fcc γ -iron at 1400 C, which again to bcc α -iron at 906 C.
- Pure metals generally possess:
 - Excellent thermal and electrical conductivity. Ex: Al, Cu, etc.
 - Higher ductility, higher melting point, lower yield point and tensile strength.
 - Better corrosion resistance as compared to alloys.

Solidification of pure metals:

- Because of high melting points, pure metals exhibit, certain difficulties in casting:
 - Difficulty in pouring.
 - Occurrence of severe metal mould reaction.
 - Greater tendency towards cracking.
 - Produce defective castings.

Solidification of pure metals:



Pure metals melt and solidify at the single temp which may be termed as the freezing point or solidification point, as in the fig the area above the freezing point the metal is liquid and below the freezing point (F.P) the metal is in the solid state.

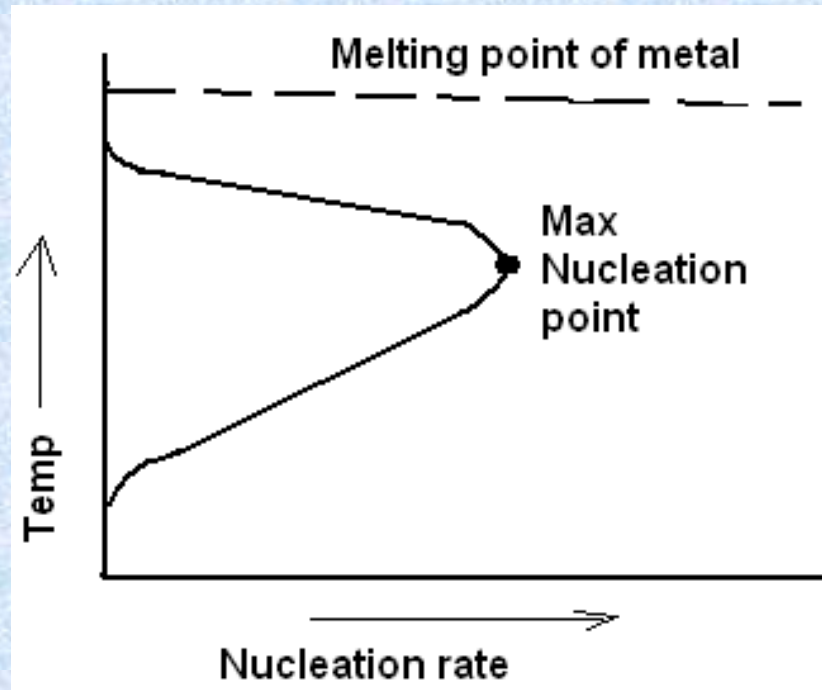
Nucleation and Grain growth:

Nucleation

- It is the beginning of phase transformation nucleation may involve:
 - a) Assembly of proper kinds of atoms by diffusion.
 - b) Structural change into one or more unstable intermediate structures.
 - c) Formation of critical size particle (nuclei) of the new phase (solid phase).
- Nucleation of super cooled grains is governed by two factors:
 - i. Free energy available from solidification process. This depends on the volume of the article formed.
 - ii. Energy required to form a liquid to solid inter phase. This depends on the surface area of particle.

The above explanation represents Homogenous or self nucleation [occurs in perfect homogenous material (pure metals)]

Nucleation



From the fig:

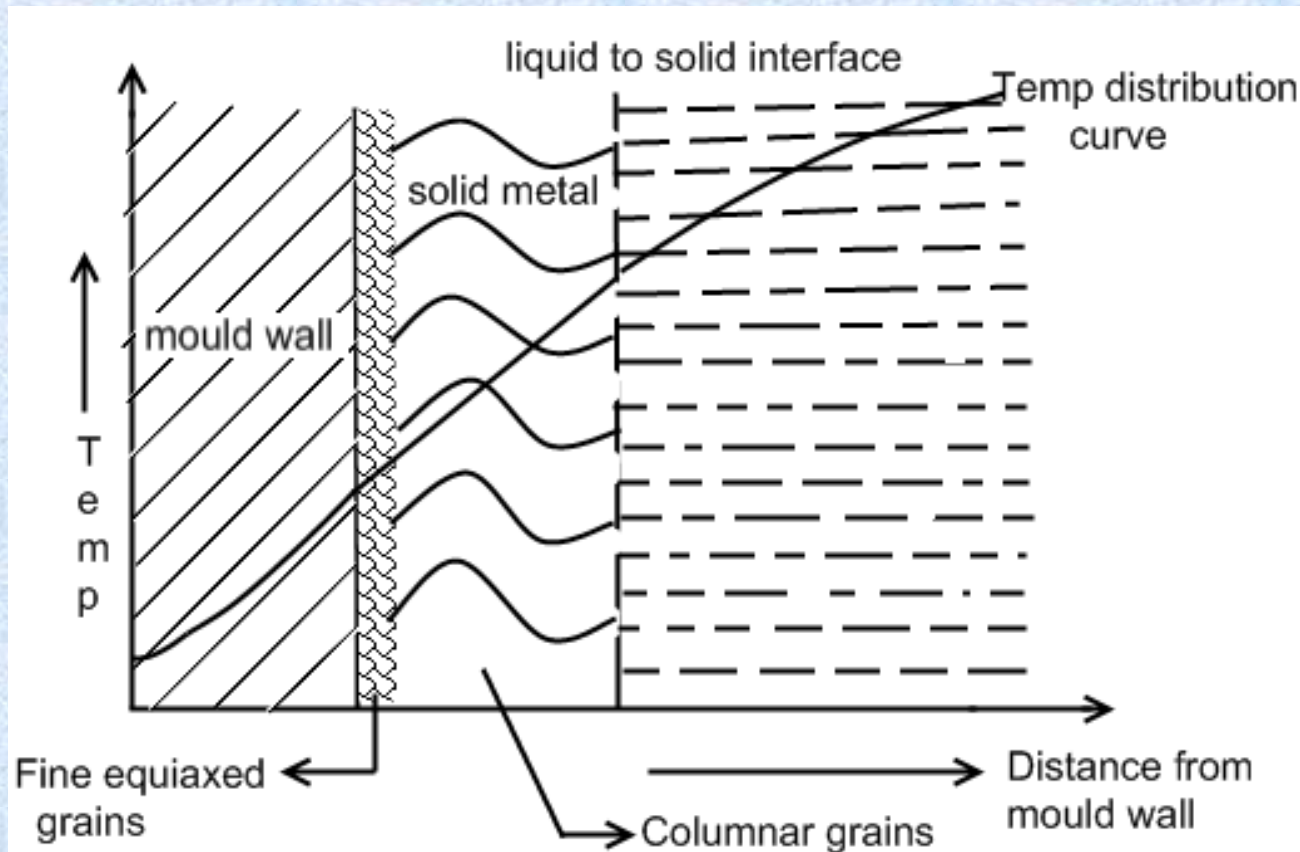
- i) as the temp drops nucleation rate increases.
- ii) Nucleation rate is max at a point considerable below the melting point.

Heterogeneous nucleation occurs when foreign particles are present in the casting which alters the liquid to solid inter phase energy, thus lowering the free energy. This affects the rate of nucleation

Grain/crystal growth:

- Grain growth may be defined as the increase of nucleases in size.
- Grain growth follows nucleation during this phase the nuclei grow by addition of atoms.
- The nuclei reduce their total free energy by continuous growth.
- From the fig, it seems that the grain growth starts from the mould wall more over since there is a temp gradient growth occurs in a direction opposite to the heat flow. That is towards the center of the melt.

Grain/crystal growth:



Continuous Casting and Ingot Casting

- **Ingot casting** - The process of casting ingots. This is different from the continuous casting route.
- **Continuous casting** - A process to convert molten metal or an alloy into a semi-finished product such as a slab.

Steel making Process

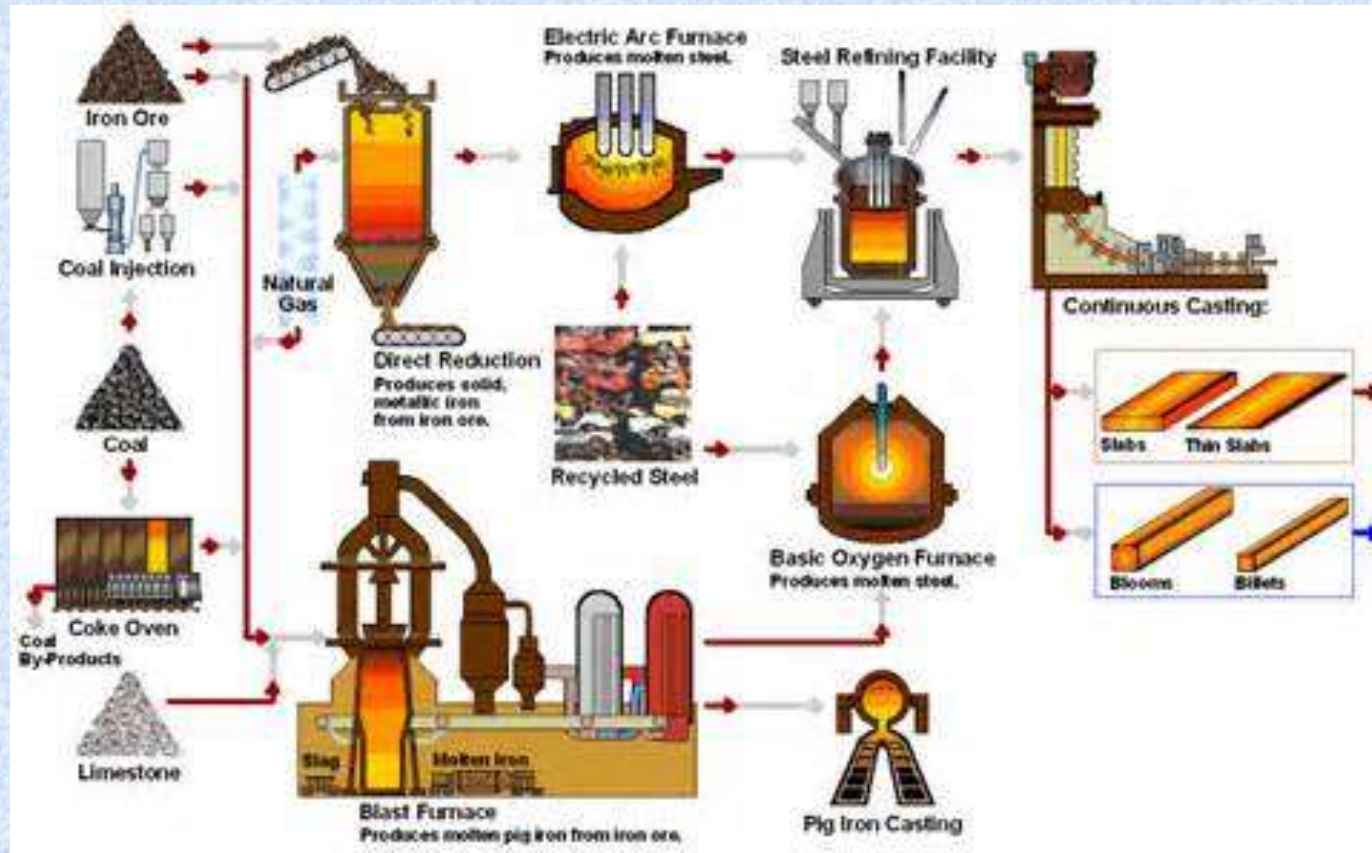


Fig: Summary of steps in the extraction of steels using iron ores, coke and limestone. (Source: www.steel.org.)

Rapid Solidification

- **Rapid Solidification or Melt spinning** is a technique used for rapid cooling of liquids.
- A wheel is cooled internally, usually by water or liquids nitrogen, and rotated.
- A thin stream of liquid is then dripped onto the wheel and cooled, causing rapid solidification.
- This technique is used to develop materials that require extremely high cooling rates in order to form, such as metallic glasses.
- The cooling rates achievable by melt-spinning are on the order of 10^4 – 10^7 kelvind per second (K/s).

Zone refining

- **Zone melting** (or **zone refining** or **floating zone process**) is a group of similar methods of purifying crystals, in which a narrow region of a crystal is molten, and this molten zone is moved along the crystal.
- The molten region melts impure solid at its forward edge and leaves a wake of purer material solidified behind it as it moves through the ingot.
- The impurities concentrate in the melt, and are moved to one end of the ingot.