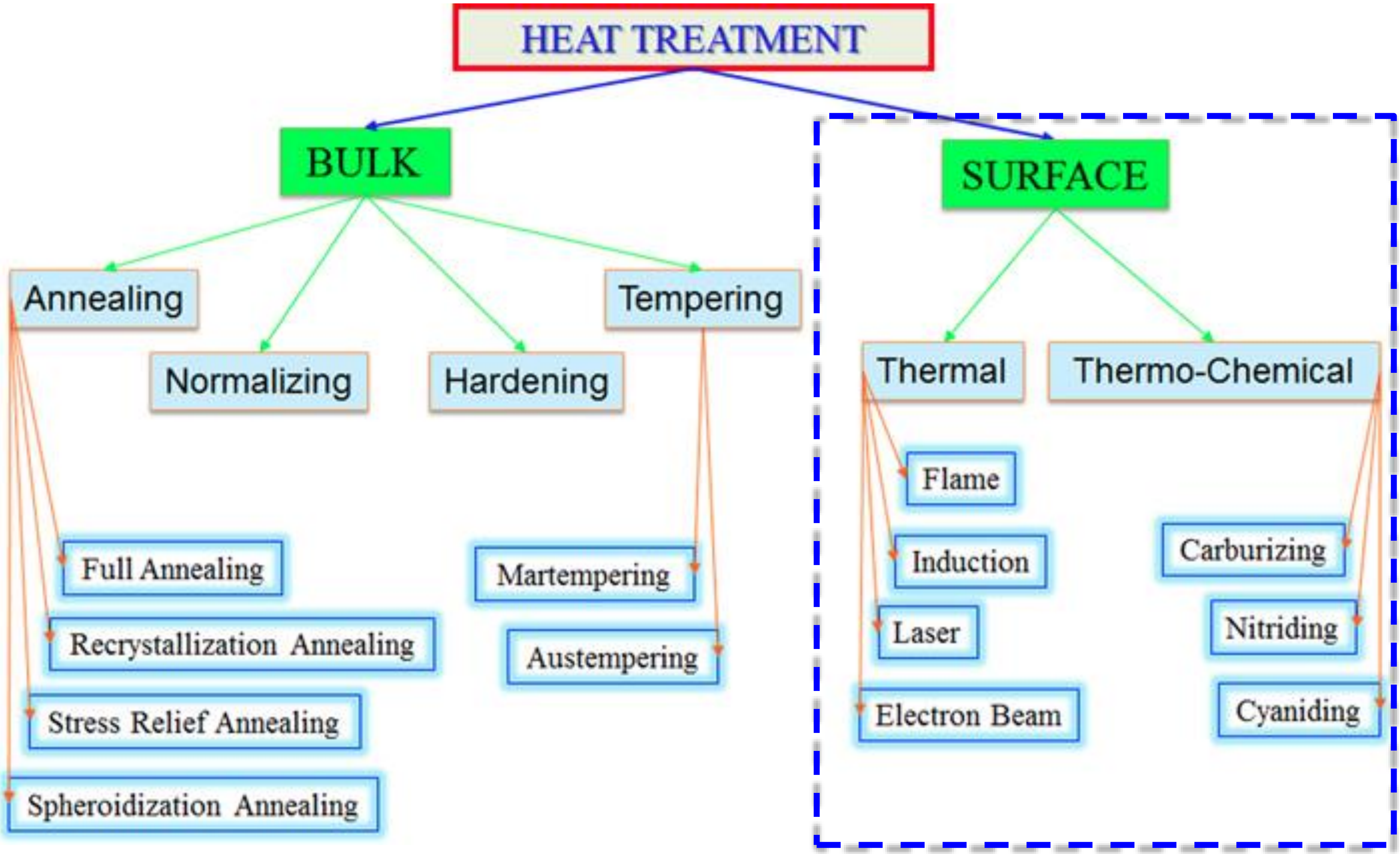
Basic classification



Surface or case hardening

- Many industrial applications require a hard wear resistant surface called case, and a relatively soft, tough inside called core
- Hardening only the outer surface of the steel component to enhance its fatigue and wear resistance is known as surface or case hardening
- Depending upon the process-route, case hardening can be classified as:

Thermal: involving no change of chemical composition; e.g. Flame hardening, induction hardening etc.

Thermochemical: Involving a change of chemical composition at the surface; e.g. carburizing, nitriding, cyaniding

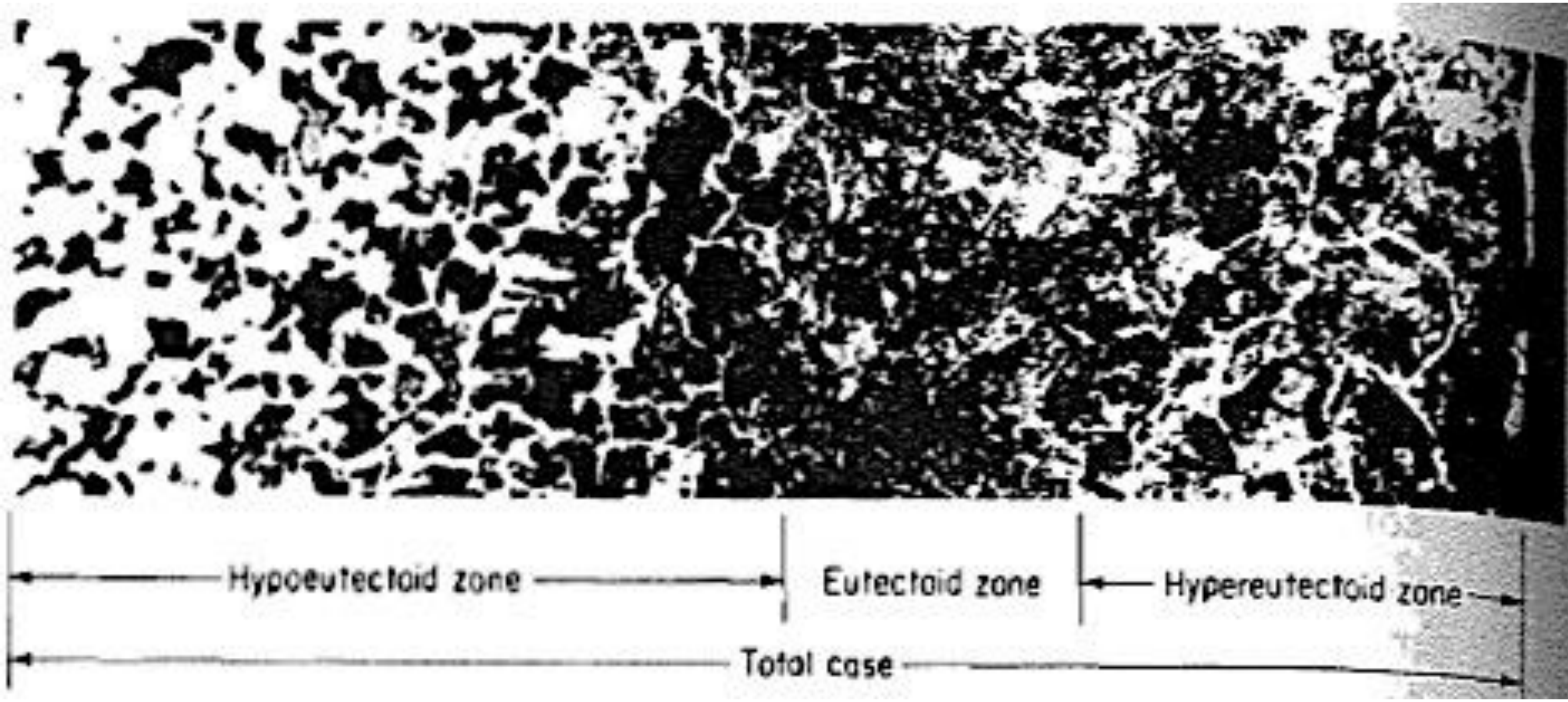
Carburizing

- A low carbon steel containing ≤ 0.2 wt.% C is placed in an atmosphere saturated with carbon at a temperature in the range of 900 - 950 °C.
- At this high temperature carbon diffusion in the austenitic surface layer takes place very quickly and a surface layer of high carbon is built up.
- As the core has a low C-content, carbon starts diffusing from the surface towards the core.
- At any temperature, the rate of C-diffusion towards the core is dependent upon the diffusion coefficient and concentration gradient.
- After holding to obtain the specified case depth, the part is removed from furnace and cooled

Carburizing

- Microstructural observation of the carburized cross-section shows three regions:
  - Hypereutectoid zone at the surface consisting of pearlite and white cementite network
  - Intermediate eutectoid zone of only pearlite
  - Finally the hypoeutectoid zone of ferrite and pearlite, with the amount of ferrite increases as the depth increases

Carburizing



Microstructure evolution in carburizing for a 0.20% C steel, carburized at 930 °C for 6 hours and furnace cooled

Carburizing

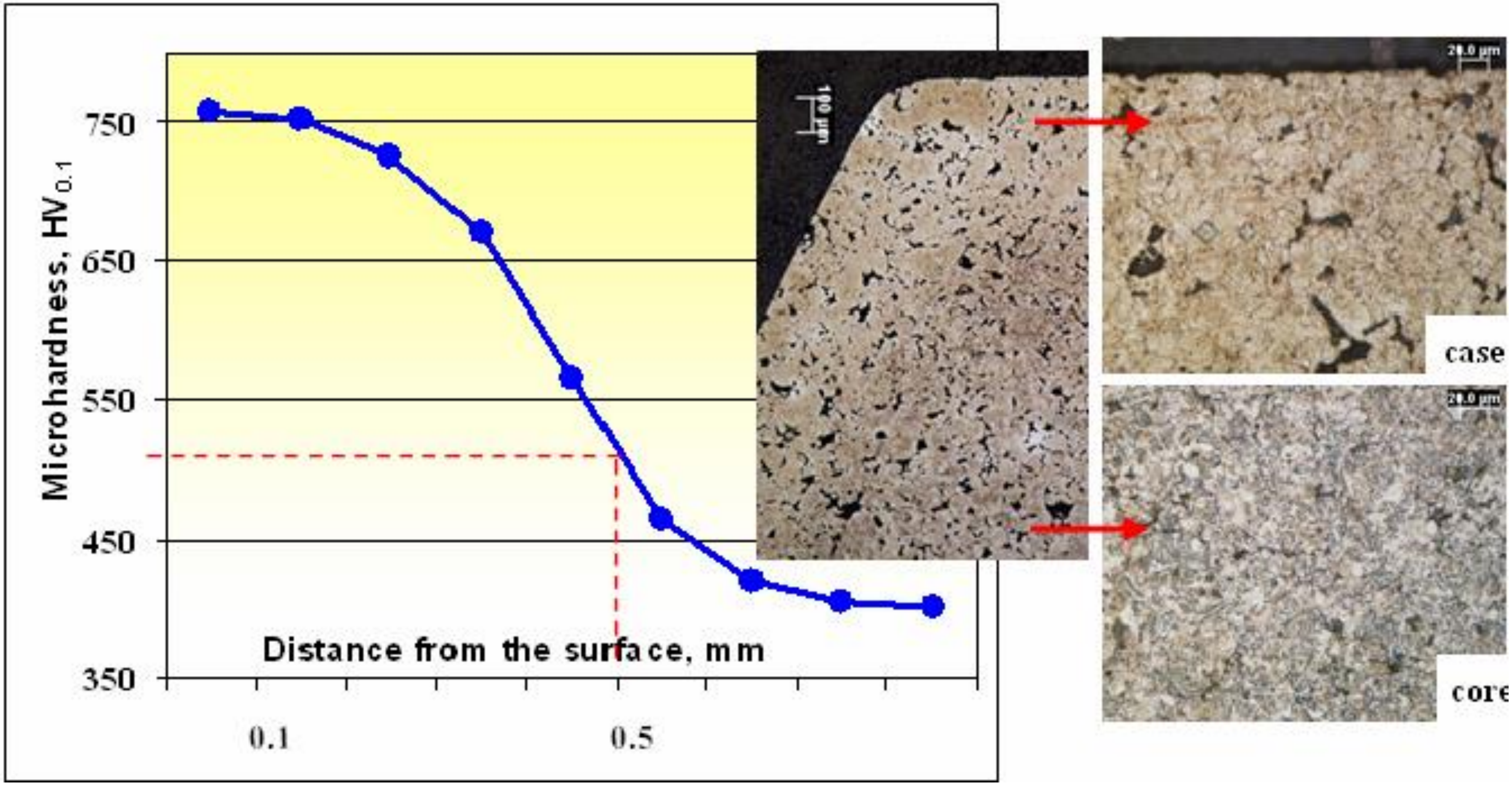
Commercially the introduction of carbon to the surface of the parts may be carried out by solid, liquid or gas carburizing media:

Solid state: Also known as pack carburizing. The workpiece is covered in graphite powder and heated at 900 – 950 °C, where the C-diffusion is very rapid.

Liquid state: In liquid carburizing, the workpiece is immersed in a bath of carburizing salts at the required temperature

Gaseous state: In gas carburizing, the workpiece is placed inside a furnace with a controlled gas atmosphere, which provides the necessary C-potential.

Carburizing



Microstructure and microhardness profile of a carburized gear

MATERIALS ENGINEERING
MT30001
3-0-0

Offered by:

Metallurgical & Materials Engineering Dept.

Instructors:

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Common iron based alloys and steel specifications

Content of this course

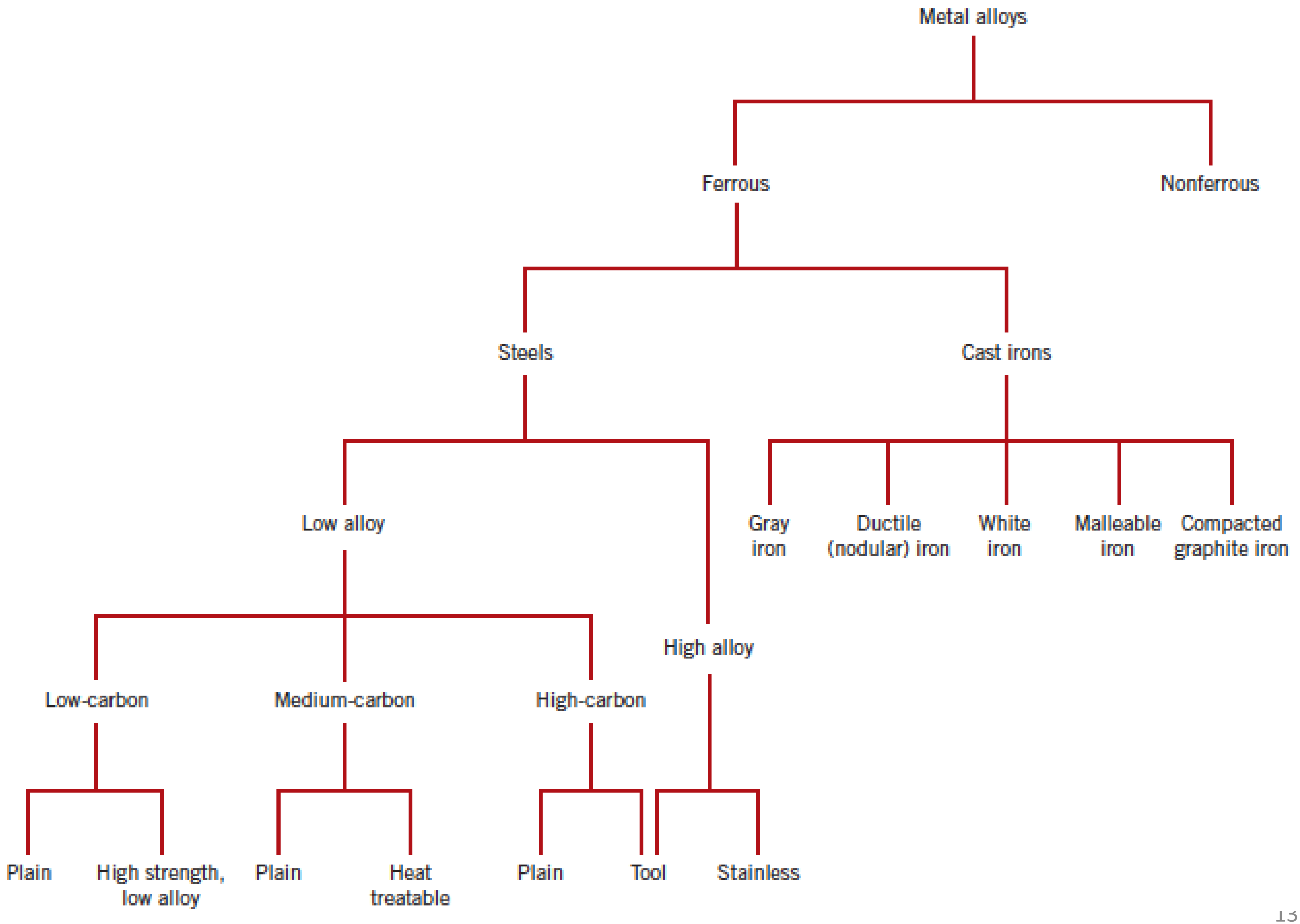
- Classification of ferrous alloys
- Plain carbon steels
- Effect of alloying elements in steel
- Stainless steels
- Some technically important alloy steels
- Cast irons

Textbooks referred to:

- Introduction to Physical Metallurgy – S. H. Avner
- Materials Science and Engineering an Introduction – W. D. Callister

Majority of the images in this course have been collected from different textbooks and scientific documents available in internet. They are not from my own research and have been used solely here for teaching purpose

Classification of ferrous alloys

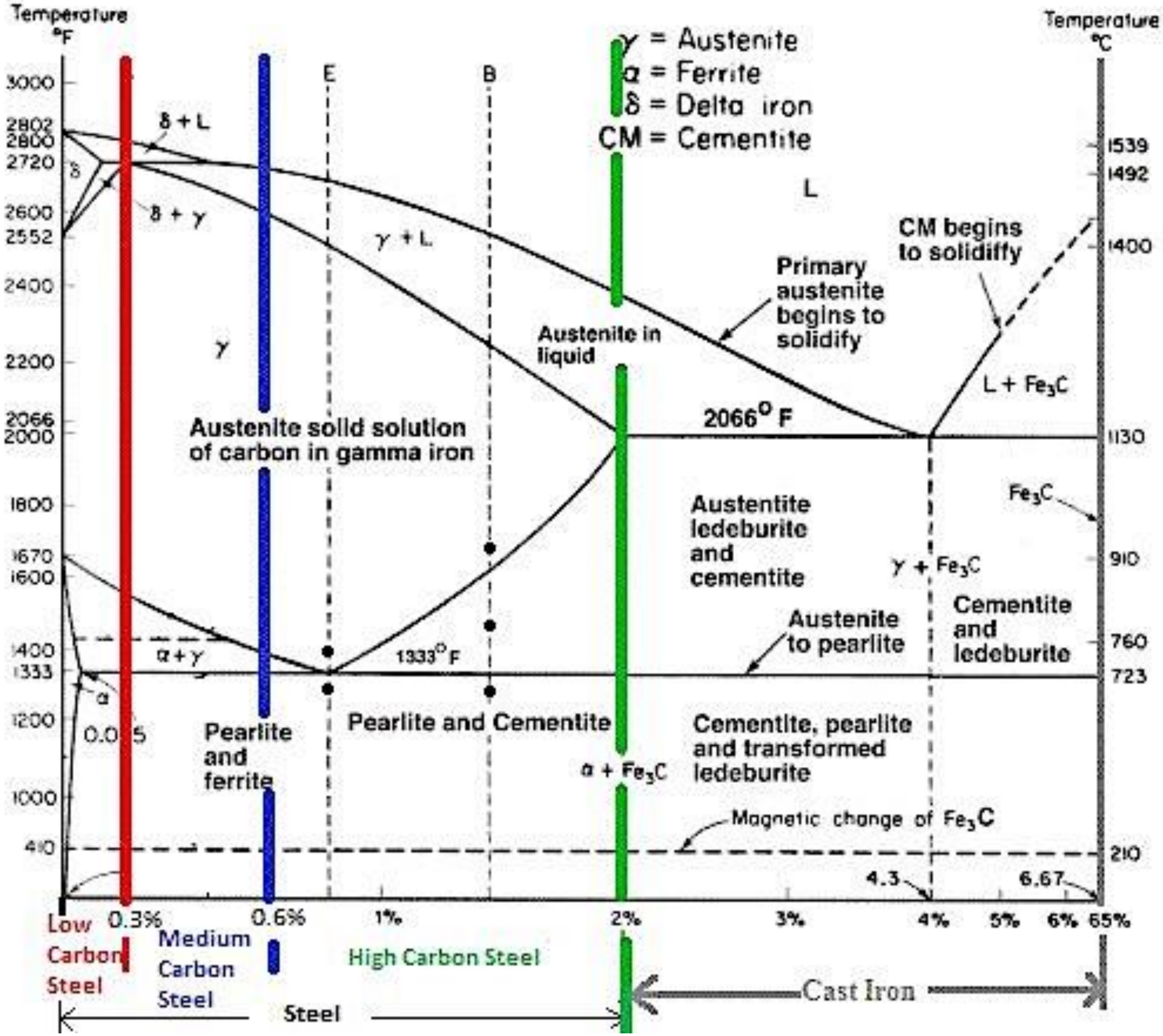


Classification of ferrous alloys

Ferrous alloys are broadly classified into two groups:

- Iron carbon alloys containing < 2.1 wt.% C are called steels. In practice however steels rarely contain > 1.4 wt.% C
- Iron carbon alloys containing between 2.1 wt.% and 6.7 wt.% C are called cast irons. Commercial cast irons however normally contain max. 4.5 wt.% C

Classification of ferrous alloys



Classification of ferrous alloys

Steels are further classified into two broad groups:

- Low alloy alloy steels containing a total alloying element of < 10 wt.%
- If the total alloying element content of steel > 10 wt.%, it is known as high alloyed steel.

Depending upon C-content, low alloy steels are further classified as:

- Low carbon steel: C-content < 0.25 wt.%
- Medium carbon steel: 0.25 wt.% < C-content < 0.60 wt.%
- High carbon steel: 0.60 wt.% < C-content < 1.40 wt.%

Low carbon steels

- Of all the different steels, they are produced in the greatest quantities
- They contain < 0.25 wt.% C and are unresponsive to heat treatments intended to form martensite.
- Strengthening in these steels is accomplished by cold working
- Microstructure of low carbon steels consists of a mixture of ferrite and pearlite
- Low carbon steels are relatively soft and weak, but have outstanding ductility and toughness. Moreover they are easily machinable and weldable and they are cheapest to produce.

Low carbon steels

Typical applications of low carbon steels

- Automobile body components
- Structural shapes such as I-beams, channels etc.
- Sheets used in pipelines, bridges, buildings etc.

Typical mechanical properties

Yield strength: 275 MPa

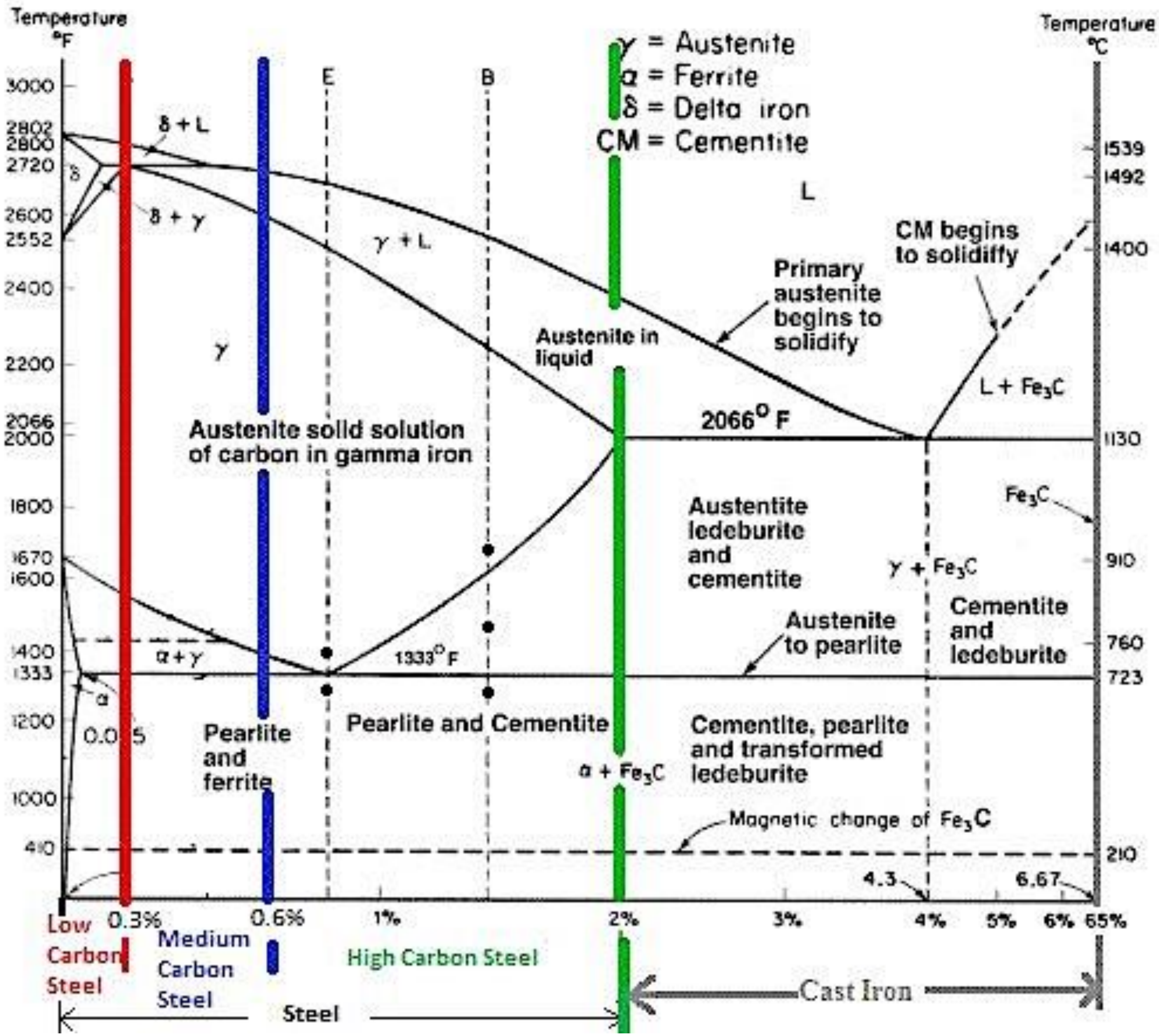
Tensile strength: 415 – 575 MPa

Elongation: 25%

Medium carbon steels

- Their C-concentration is in the range of 0.25 – 0.60 wt.%
- They are most often used in hardened and tempered condition, having microstructure of tempered martensite.
- Plain medium carbon steels have limited hardenability; addition of alloying elements like Cr, Mo and Ni enhance the hardenability.
- These steels are stronger than plain carbon steels but possess reduced toughness and ductility.
- Applications include railway wheels and tracks, gears, crankshafts, machine parts etc.

Classification of ferrous alloys



Mechanical Properties of Medium Carbon Steels

AISI	Type	Special properties	Heat Treatment	Yield MPa	UTS MPa	Elong %	BHN
1040	Plain carbon	Medium strength	Normalized	374	589	28	201
			Quench & Temper	593	779	19	262
1340	Mn Steel	High strength as normalized	Normalized	558	836	22	248
			Quench & Temper	1593	1806	11	505
2340	Ni Steel	Medium strength + LT toughness	Normalized	490	722	22	205
			Quench & Temper	776	883	19	248
3140	Cr-Ni Steel	Medium strength + corrosion resistance	Normalized	485	770	22	212
			Quench & Temper	766	883	20	248
4140	Cr-Mo steel	High temperature strength	Normalized	655	1020	18	302
			Quench & Temper	1641	1772	8	510
4340	Ni-Cr-Mo steel	Highest strength + toughness	Normalized	861	1279	36	363
			Quench & Temper	1675	1875	10	520
5140	Cr steel	High strength + corrosion resistance	Normalized	427	793	23	229
			Quench & Temper	1641	1793	9	490
6140	Cr-V Steel	High temperature strength	Normalized	615	939	22	269
			Quench & Temper	1689	1931	1	610

High carbon steels

- High carbon steels normally have C-content in the range of 0.60 – 1.40 wt.%
- They are the hardest, strongest and least ductile of all carbon steels.
- These steels are almost always used in the hardened and tempered condition and have excellent wear resistance.
- High carbon versions of these steels contain Cr, V, W and Mo as alloying elements. These alloying elements combine with C to form very hard and wear resistant carbides.
- High C steels are used as cutting tools, dies as well as in knives, blades, springs etc.

Purpose of forming alloy steels

There are several purposes why alloy steels are formed:

- Increase in hardenability
- Improvement of strength and other mechanical properties at low and high temperatures
- Improvement of toughness without affecting its strength
- Increase corrosion resistance
- Increase wear resistance

Effectivity of alloying is always an interplay between property enhancement and cost factor.

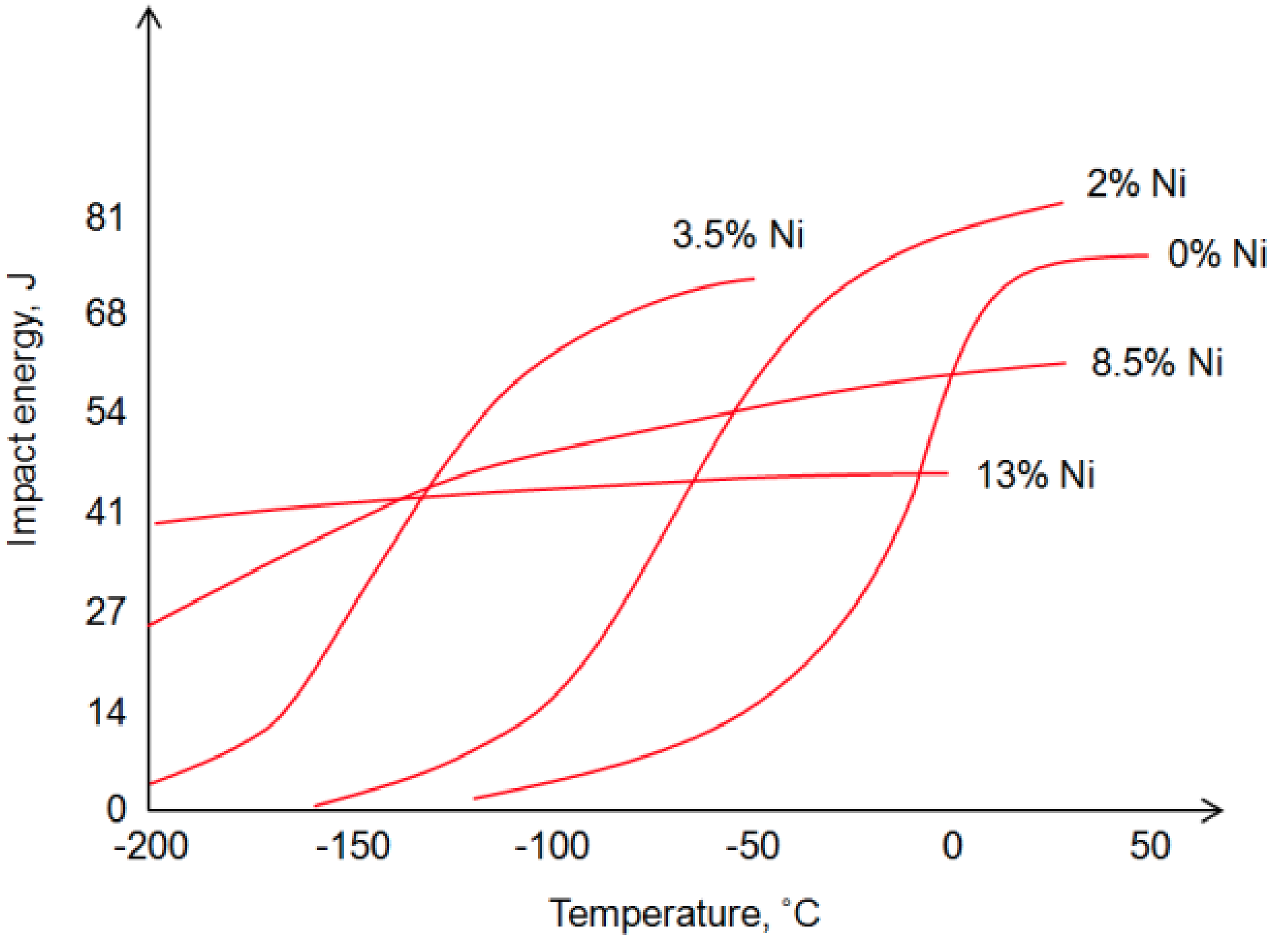
Effect of certain alloying elements

Nickel steels

- Nickel lowers the critical temperatures, widens the temperature range for heat treatment, retards austenite decomposition and does not form carbides.
- For a given C-level, strength of nickel steels is higher ➔ increased toughness and fatigue resistance
- Nickel has a minor effect on hardenability but is outstanding in enhancing toughness at low temperature

Effect of certain alloying elements

Nickel steels



Effect of Ni on impact energy of low C steel

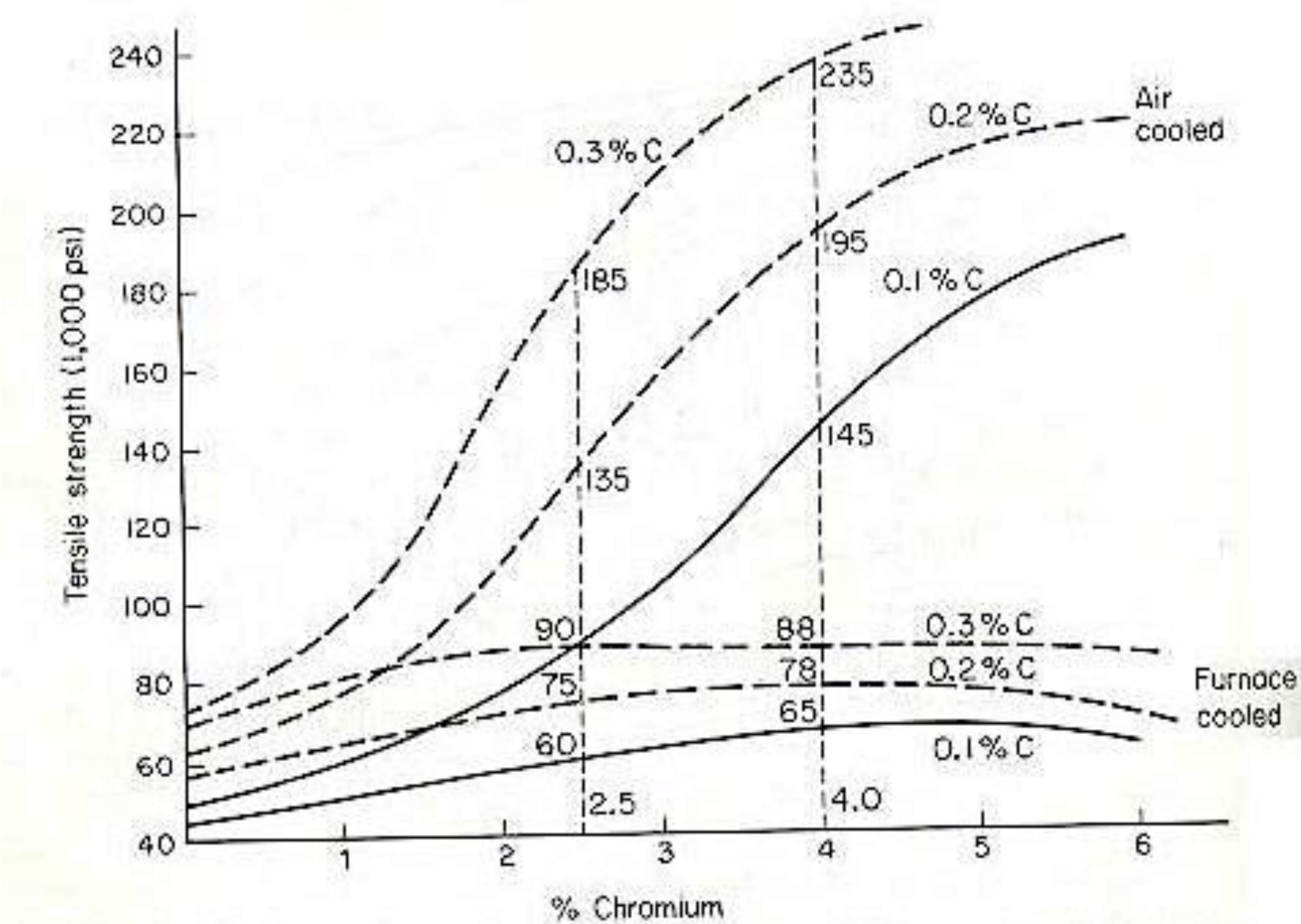
Effect of certain alloying elements

Chromium steels

- Chromium is a less expensive alloying element than nickel and forms carbides
- These carbides have high hardness and good wear resistance
- In low carbon steels, chromium tends to go into solution, thereby increasing the strength and toughness
- When Cr-content > 5 wt.%, high temperature properties and corrosion resistance are improved. Steels containing > 11 wt.% Cr are corrosion resistant and known as stainless steel

Effect of certain alloying elements

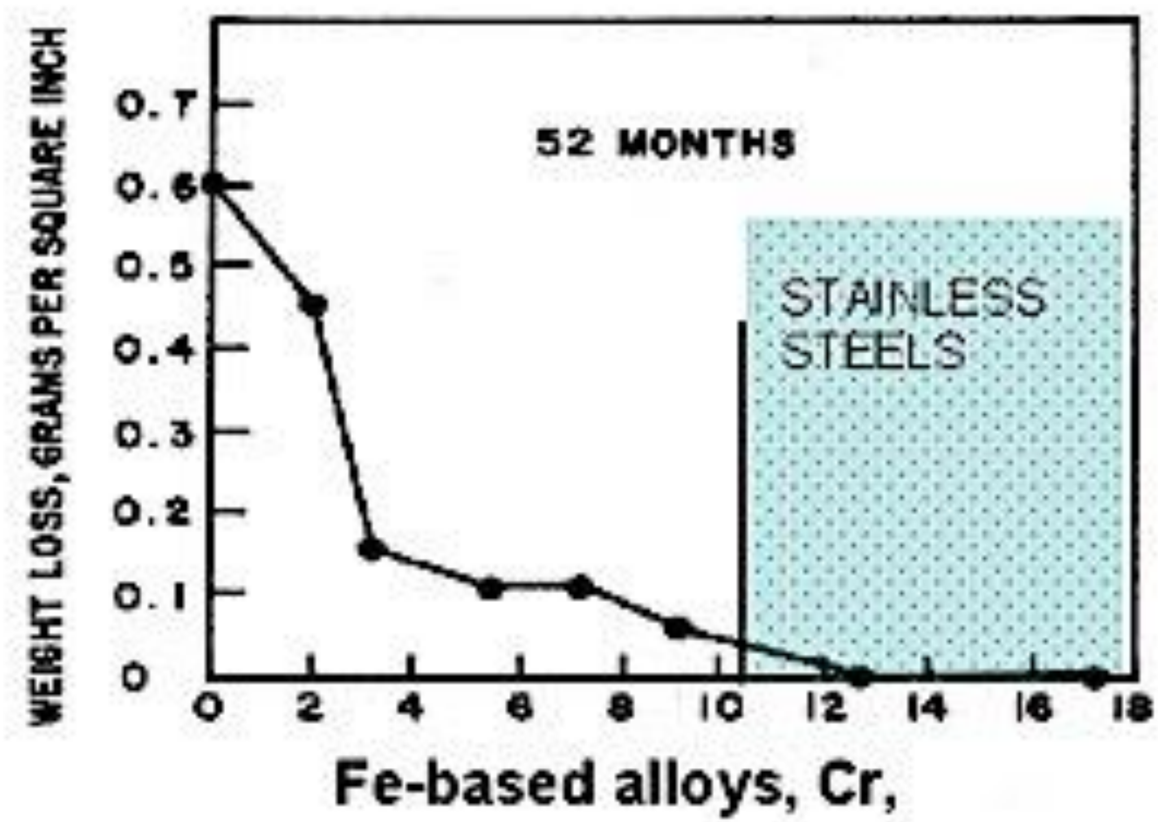
Chromium steels



Effect of Chromium in Annealed and Air-cooled Steels

Effect of certain alloying elements

Chromium steels



Effect of Cr-content on corrosion resistance of steel in one environment

Effect of certain alloying elements

Nickel-Chromium steels

- In these steels the ratio of nickel to chromium is approximately 2.5 to 1
- A combination of alloying elements usually imparts some of the properties of both elements
- Nickel contributes to the increase in ductility and toughness
- This is combined with the effect of chromium in increasing the hardenability

Effect of certain alloying elements

Manganese steels

- Manganese is one of the cheapest alloying elements and is present in all steels as deoxidizer.
- Manganese reduces the tendency to hot shortness in steels – in the absence of manganese, iron forms FeS with suphur. This forms as a thin continuous film. During rolling of steel, this film becomes liquid and may crack the steel along grain boundaries. When manganese is present in steel it forms MnS, which has a much higher melting point and hence does not adversely affect the steel during hot forming.

Effect of certain alloying elements

Molybdenum steels

- Molybdenum is a relatively expensive alloying element
- It is a very strong carbide former
- It has a very strong effect on hardenability and like chromium, it also increases the high temperature hardness and strength of steels
- For carburizing, molybdenum increases the wear resistance of the case and toughness of the core.

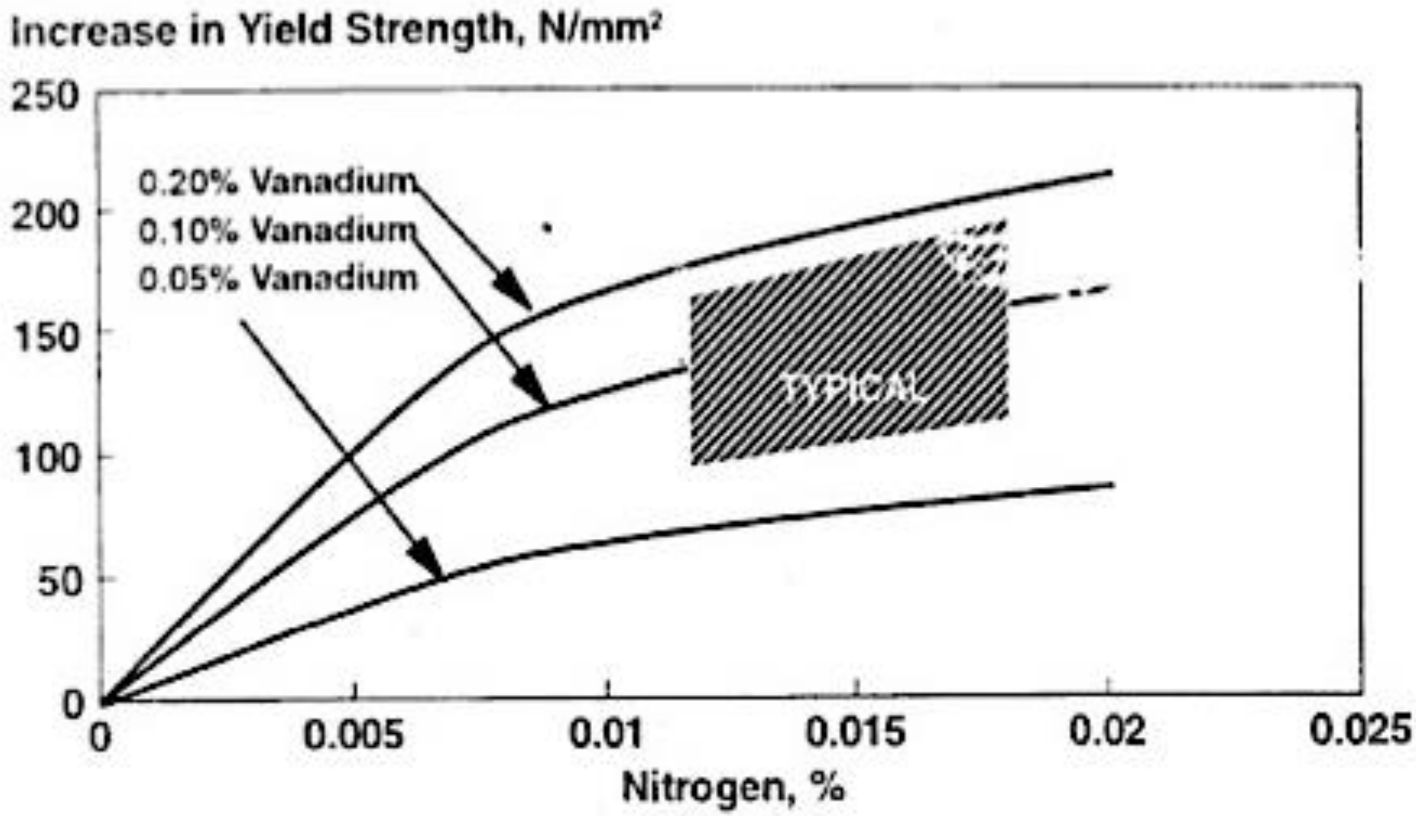
Effect of certain alloying elements

Vanadium steels

- Vanadium is the most expensive alloying element in steel
- It is a powerful deoxidizer and strong carbide former and it resists grain growth.
- About 0.05 wt.% vanadium in steel produces a sound, uniform, fine grain casting
- When dissolved in solid solution, vanadium has a marked effect on hardenability, yielding high mechanical properties on air cooling
- Carbon vanadium steels are used for heavy machinery forgings that are air cooled

Effect of certain alloying elements

Vanadium steels

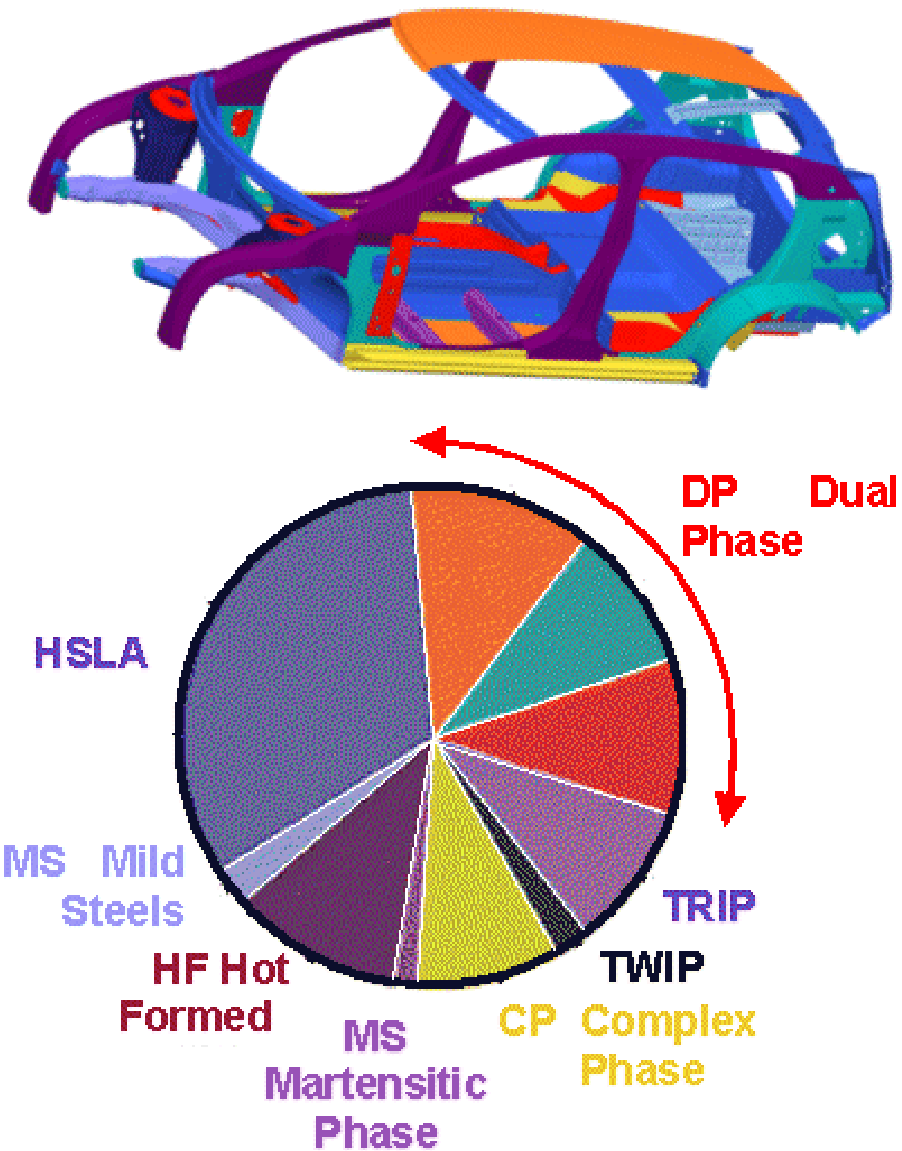


Increase in yield strength from vanadium and nitrogen as a result of formation of vanadium nitride

High Strength Low Alloy (HSLA) steels

- HSLA steels or microalloyed steels are aimed to provide better mechanical properties and/or greater resistance to atmospheric corrosion than conventional steels.
- These steels contain low carbon content in the range of 0.05 – 0.25 wt.% and Mn upto about 2 wt.%. Small quantities of Cr, Mo, Ni, Cu, V, Nb, N, Zr and Ti are added to enhance several properties
- HSLA steels typically have yield strength > 275 MPa and tensile strength > 480 MPa.
- Applications include oil and gas industries, industrial equipment, bridges, maschinery etc.
- The higher strength/weight ratio of HSLA steels make them very attractive in automobile industry

High Strength Low Alloy (HSLA) steels



Kinds of steel used in modern cars

Strengthening of HSLA steels

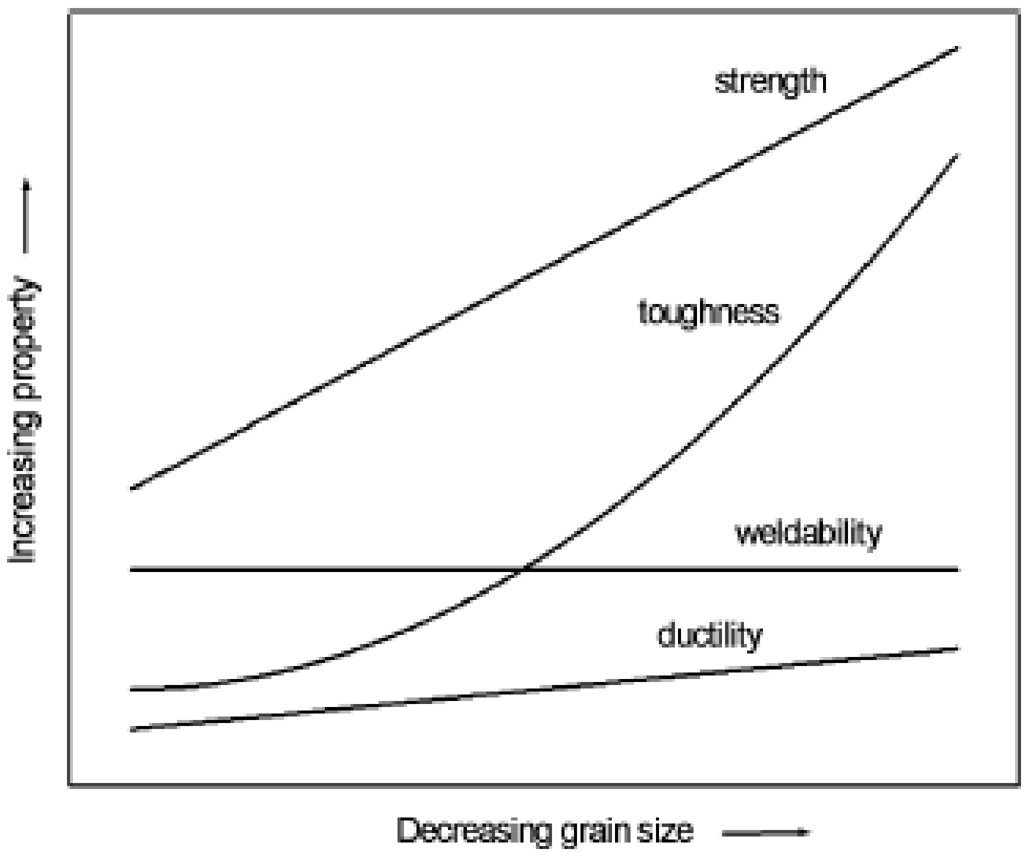
The emphasis of fabrication of HSLA steels is to have optimum combination between strength, toughness, ductility and formability.

The dominant mechanisms of strengthening in HSLA steels are:

- Grain boundary strengthening resulting from a reduction in grain size and
- Precipitation strengthening

Strengthening by grain refinement

- Grain refinement is an effect of microalloying of steels and it simultaneously produces increased strength and toughness, without affecting the ductility and weldability.



Effect of ferrite grain size on properties of steel

Strengthening by grain refinement

Strengthening due to grain refining follows the Hall-Petch relation:

$$\sigma_y = \sigma_0 + k \cdot d^{-\frac{1}{2}}$$

Where σ_y is the yield strength and *d* is the grain size.

Grain refinement in HSLA steels is achieved by three types of precipitation:

- Small particles that pin down austenite grain boundaries during reheating – TiN, Nb(C,N) etc.
- Particles that precipitate during transformation of austenite to ferrite – V(C,N), NbC, TiC etc.
- Particles that dissolve during reheating but precipitate in austenite during hot rolling – Nb(C,N), VN etc.

Precipitation strengthening

- Precipitation strengthening is produced by particles precipitated in the ferrite phase.
- Under external loading, these particles hinder dislocation motion ➔ increase in strength
- Precipitates most commonly operating are V(C,N). Although NbC and TiC particles are also very effective.
- The content of the elements C and N, as well as the thermomechanical processing employed determine whether the particles are precipitate in ferrite or austenite.

Lecture 2

Stainless steel

Stainless steel is an alloy of Iron with a minimum of 10.5% Chromium which

- unlike carbon steels do not rust when exposed to normal atmosphere
- are resistant to concentrated acids
- do not scale at temperatures upto 1100 °C

Stainless steels are further attractive as:

- they offer good combination of mechanical properties
- have good machinability and formability
- further addition of other alloying elements (e.g. Ni, Mo, N etc.) in various amounts imparts other useful properties.

Applications of stainless steel

Domestic: Cutlery, washing machine drums, razor blades etc.

Architecture: Handrails, door fittings, reinforcement bars, cladding etc.

Transport: Exhaust systems, chemical tankers, ship containers etc.

Chemical: Pressure vessels, pipelines

Oil and gas: platform accommodation, cable trays, subsea pipelines etc.

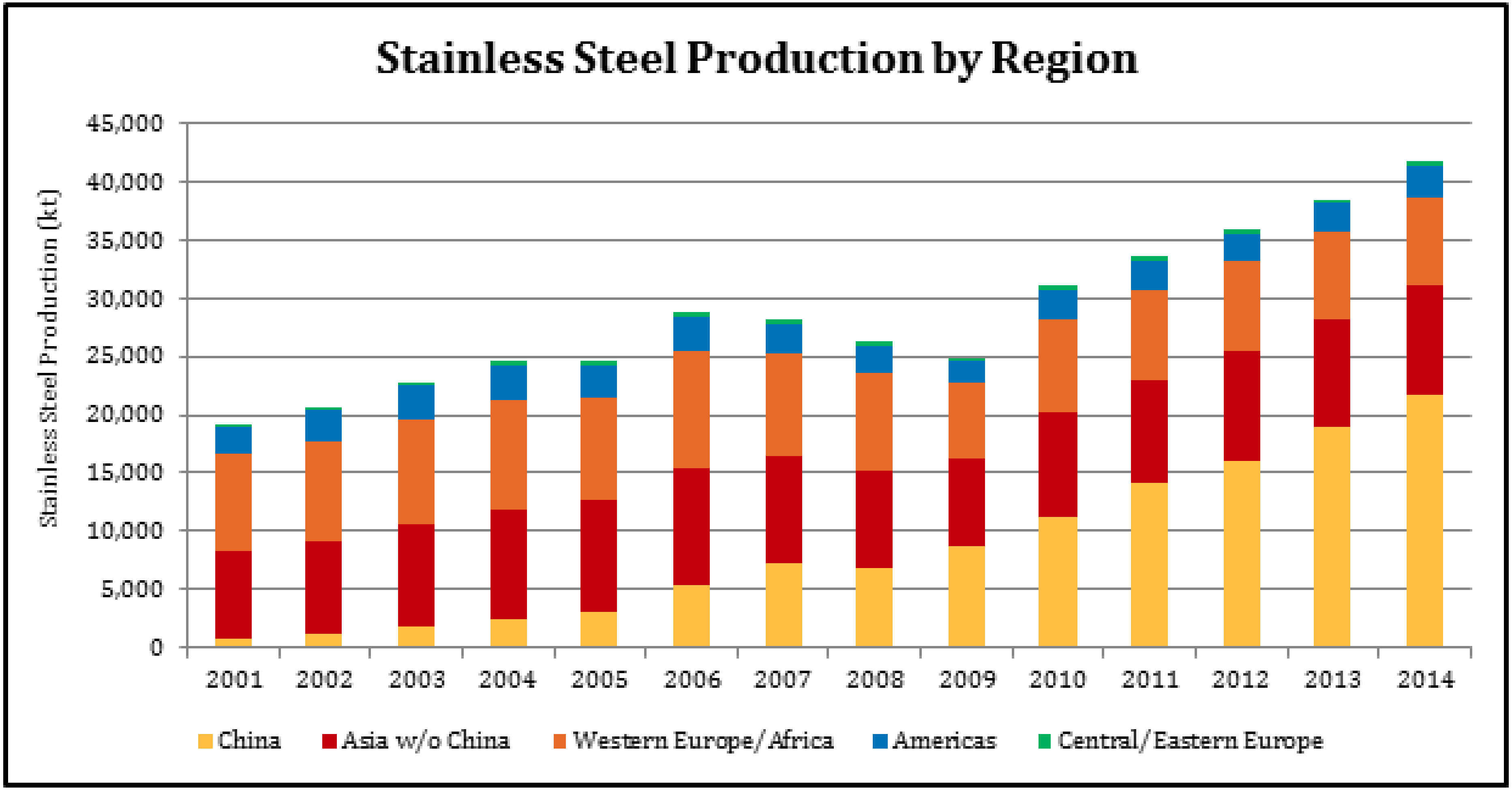
Medical: Implants, surgical instruments etc.

Food industry: Brewing, distilling, food processing industry etc.

Applications of stainless steel

Some industry types where stainless steels are commonly used

Applications of stainless steel



http://www.goldendragoncapital.com/stainless-steel-production-by-region/

Classification of stainless steel

Steel category	Composition (wt%)					Hardenable	Ferro-magnetism
	C	Cr	Ni	Mo	Others		
Martensitic	›0.10	11-14	0-1	-	V	Hardenable	Magnetic
	›0.17	16-18	0-2	0-2			
Martensitic-austenitic	‹0.10	12-18	4-6	1-2		Hardenable	Magnetic
Precipitation hardening		15-17	7-8	0-2	Al,	Hardenable	Magnetic
		12-17	4-8	0-2	Al,Cu,Ti,Nb		
Ferritic	‹0.08	12-19	0-5	‹5	Ti	Not hardenable	Magnetic
	‹0.25	24-28	-	-			
Ferritic-austenitic (duplex)	‹0.05	18-27	4-7	1-4	N, W	Not hardenable	Magnetic
Austenitic	‹0.08	16-30	8-35	0-7	N,Cu,Ti,Nb	Not hardenable	Non-magnetic

Stainless steel–main alloying elements

Chromium (Cr)

- The most important alloying element in stainless steel
- Improves corrosion resistance and high temperature oxidation resistance
- Imparts ferritic structure

Nickel (Ni)

- Promotes austenitic structure
- Enhances ductility and toughness
- Improves corrosion resistance, especially in acid environments
- In some stainless steels it forms intermetallic compounds and enhance strength

Stainless steel–main alloying elements

Molybdenum (Mo)

- It promotes a ferritic structure
- Substantially enhances the resistance to both general and localized corrosion
- Moderately increases the strength

Copper (Cu)

- Promotes austenitic structure
- Enhances corrosion resistance in certain acids
- Forms intermetallic compounds in certain stainless steels to enhance strength

Stainless steel–main alloying elements

Carbon (C)

- Strong austenite former
- Strongly reduces the resistance to intergranular corrosion
- In ferritic steels it reduces both toughness and corrosion resistance

Nitrogen (N)

- A strong austenite former
- Substantially increases the strength but reduces toughness
- In combination with molybdenum, it enhances the resistance to localized corrosion

Stainless steel–main alloying elements

Niobium (Nb) & Titanium (Ti)

- Both are string ferrite stabilizers
- Both increase the resistance to intergranular corrosion and enhance the mechanical strength at high temperatures

Ferritic stainless steel

Typical chemical composition (in wt.%)

C < 0.08, Cr: 12 – 19, Ni: 0 – 5, Mo < 5

- Ferritic steels are characterized by good corrosion properties, very good resistance to stress corrosion cracking and moderate toughness.
- Steel grades with lower C and N have improved toughness and weldability
- Toughness of thinner sections is better than thicker sections
- Typical applications: piping, heat exchanger tubes, vessels in food and paper industry. Low alloy ferritic steels are used in mild environments

Austenitic stainless steel

Typical chemical composition (in wt.%)

C < 0.08, Cr: 16 – 30, Ni: 8 – 35, Mo: 0 - 7

- Most common stainless steel
- Possesses excellent corrosion resistance, very good toughness and weldability.
- Austenitic stainless steels are generally susceptible to stress corrosion cracking
- Resistance to general corrosion, pitting and crevice corrosion increases with increasing Cr and Mo
- Typical applications: Piping systems, heat exchangers, tanks and vessels for food, paper, pulp, chemical and pharmaceutical industry

Austenitic stainless steel

- Austenitic stainless steels containing Mo are used in chloride containing environments ➔ handle sea water at moderate or elevated temperatures
- Low alloy austenitic stainless steels are used for cryogenic applications
- Good creep and oxidation resistance of austenitic stainless steels are useful for elevated temperature applications ➔ furnace components, muffles, recuperators etc.
- Austenitic stainless steels are used in specialized applications where their non-magnetic property is useful.

Martensitic stainless steel

Typical chemical composition (in wt.%)

C > 0.1 – 0.2, Cr: 11 – 18, Ni: 0 – 2, Mo: 0 - 2

- Martensitic stainless steels are characterized by high strength and limited corrosion resistance.
- An increased C-content increases strength, but degrades the toughness and weldability.
- They are resistant to damp air, steam, freshwater, alkaline solutions etc.
- They have poor resistance to pitting and crevice corrosion; however resistant to stress corrosion cracking
- Typical applications: cutlery, springs, surgical instruments, stainless constructional material etc.

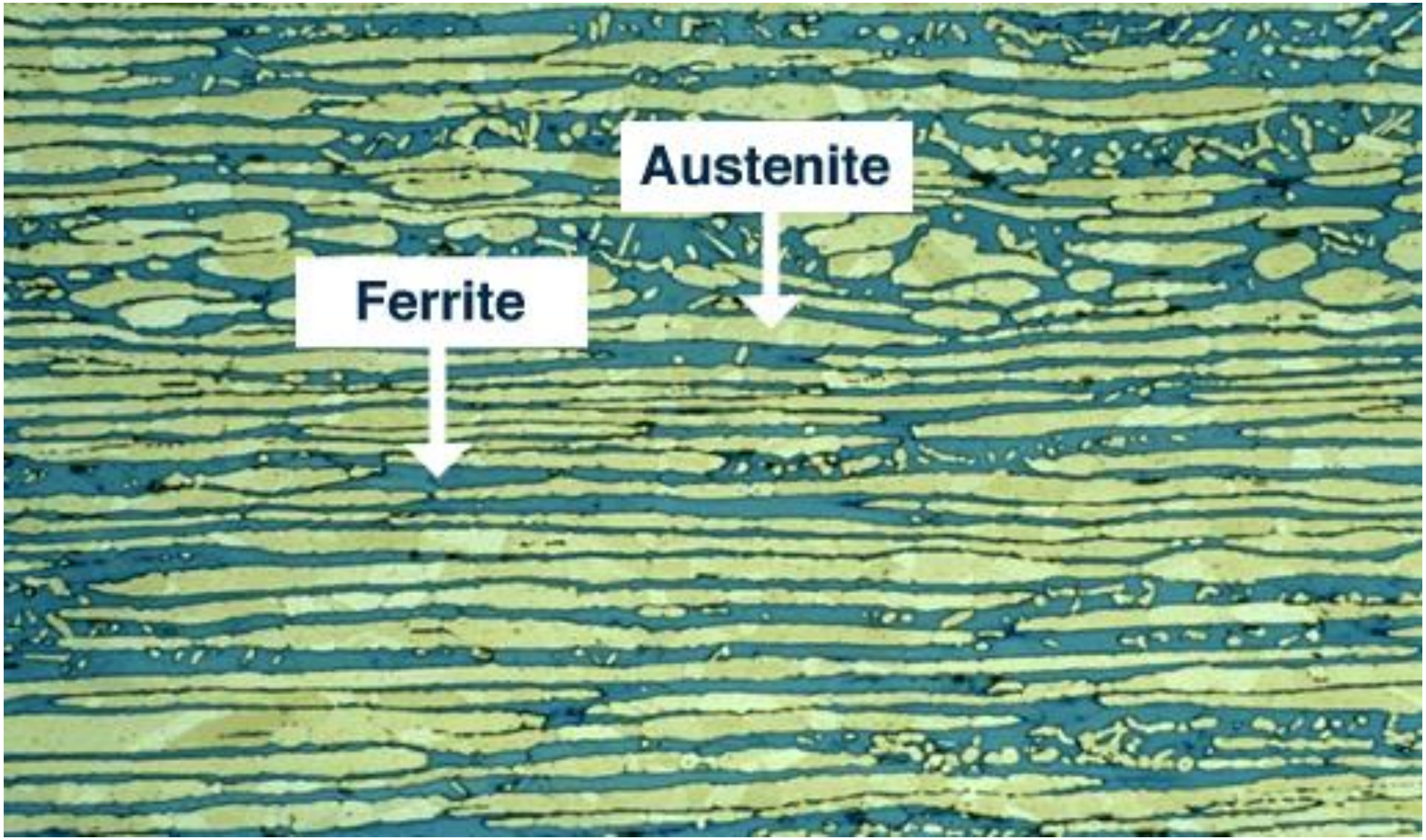
Duplex stainless steel

Typical chemical composition (in wt.%)

C < 0.05, Cr: 18 – 27, Ni: 4 – 7, Mo: 1 - 4

- Duplex stainless steels possess a chemical composition that leads to an approximately equal mixture of ferrite and austenite
- They are characterized by high strength, good toughness, very good general corrosion resistance, excellent resistance to stress corrosion cracking and corrosion fatigue
- Typical applications: pulp storage tanks, piping and process equipment in oil and gas industry, equipments for sea water applications etc.

Duplex stainless steel



Typical microstructure of a duplex stainless steel

Precipitation hardened stainless steel

Typical chemical composition (in wt.%)

Cr: 12 – 17, Ni: 4 – 8, Mo: 0 – 2, Al, Cu, Ti, Nb etc.

- They are Fe-Ni-Cr alloys containing one or more precipitation hardening elements such as Al, Ti, Cu, Nb etc. The precipitation hardening is achieved by a relatively simple aging treatment.
- The two main characteristics of all precipitation-hardening stainless steels are high strength and high corrosion resistance.
- The precipitation hardening process involves the precipitation of very fine intermetallic phases such as Ni_3Al, Ni_3Ti, $Ni_3(Al,Ti)$, NiAl, carbides etc.

Different stainless steels comparison

CHARACTERISTICS AND PROPERTIES OF STAINLESS STEELS					
	AUSTENITIC	FERRITIC	MARTENSITIC	PRECIPITATION HARDENING	DUPLEX
Magnetic Response[1]	Generally No	Yes	Yes	Yes	Yes
Weldability	Very High	Low	Low	High	High
High Temp. Resistance	Very High	High	Low	Low	Low
Low Temp. Resistance[2]	Very High	Low	Low	Low	Medium
Ductility	Very High	Medium	Low	Medium	Medium
Work Hardening Rate	Very High	Medium	Medium	Medium	Medium
Hardenable	By Cold Work	No	Quench & Temper	Age Harden	No
Corrosion Resistance[3]	High	Medium	Medium	Medium	Very High

1. Attraction of steel to a magnet. Note some grades can be attracted to a magnet if cold worked.
2. Measured by toughness or ductility at sub-zero temperatures. Austenitic grades retain ductility to cryogenic temperatures.
3. Varies significantly within between grades within each group e.g. free machining grades have lower corrosion resistance, those grades higher in molybdenum have higher corrosion resistance.

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Corrosion of stainless steel

Passivity

The reason for the good corrosion resistance of stainless steel is that they form a very thin, invisible surface film of chromium oxide in oxidizing environments. This film protects the steel from attack in aggressive environments. This protective film is called a passive film.

A stainless steel must be oxidized to form the passive film. The more oxidizing the environment, the more oxidizing agents are needed. Continuous supply of the oxidizing agent is necessary to maintain the passive film. Due to this, stainless steels are most suitable in oxidizing, neutral or mildly reducing environments. They are not resistant in strong reducing environments like hydrochloric acid.

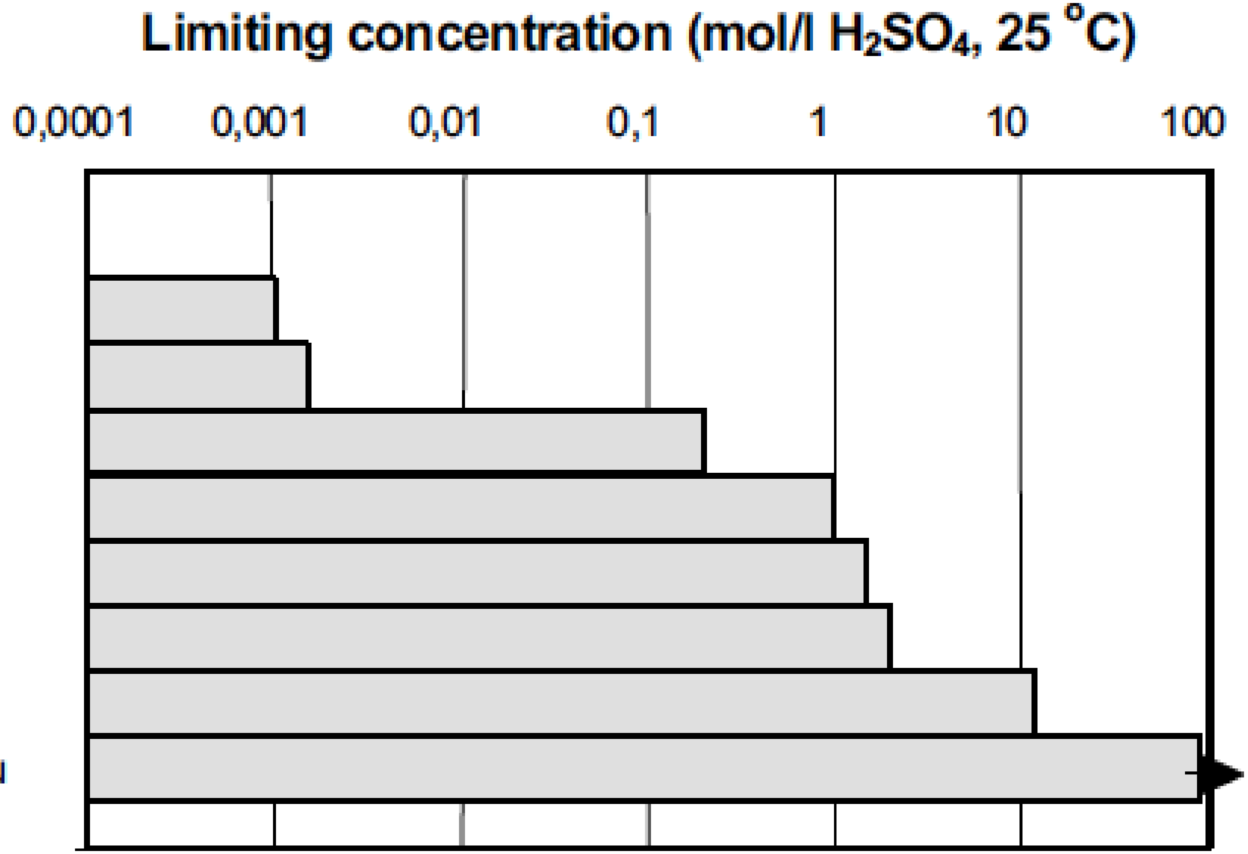
General corrosion of stainless steel

- This type of corrosion is characterised by a more or less even loss of material from the whole surface or relatively large parts of it.
- General corrosion of stainless steels normally only occurs in acids and hot caustic solutions.
- The corrosion resistance normally increases with increasing levels of Cr, Ni and Mo additions
- The aggressivity of an environment on stainless steel generally increases with increasing temperature

General corrosion of stainless steel

Steel Grade	Cr	Ni	Mo
410S	13	-	-
440C	17	-	-
304	18	9	-
316	17	12	2,7
329	25	5	1,5
'2205'	22	6	3
'254 SMO'	20	18	6,2
'904L'	20	25	4,5+Cu

Composition (%)



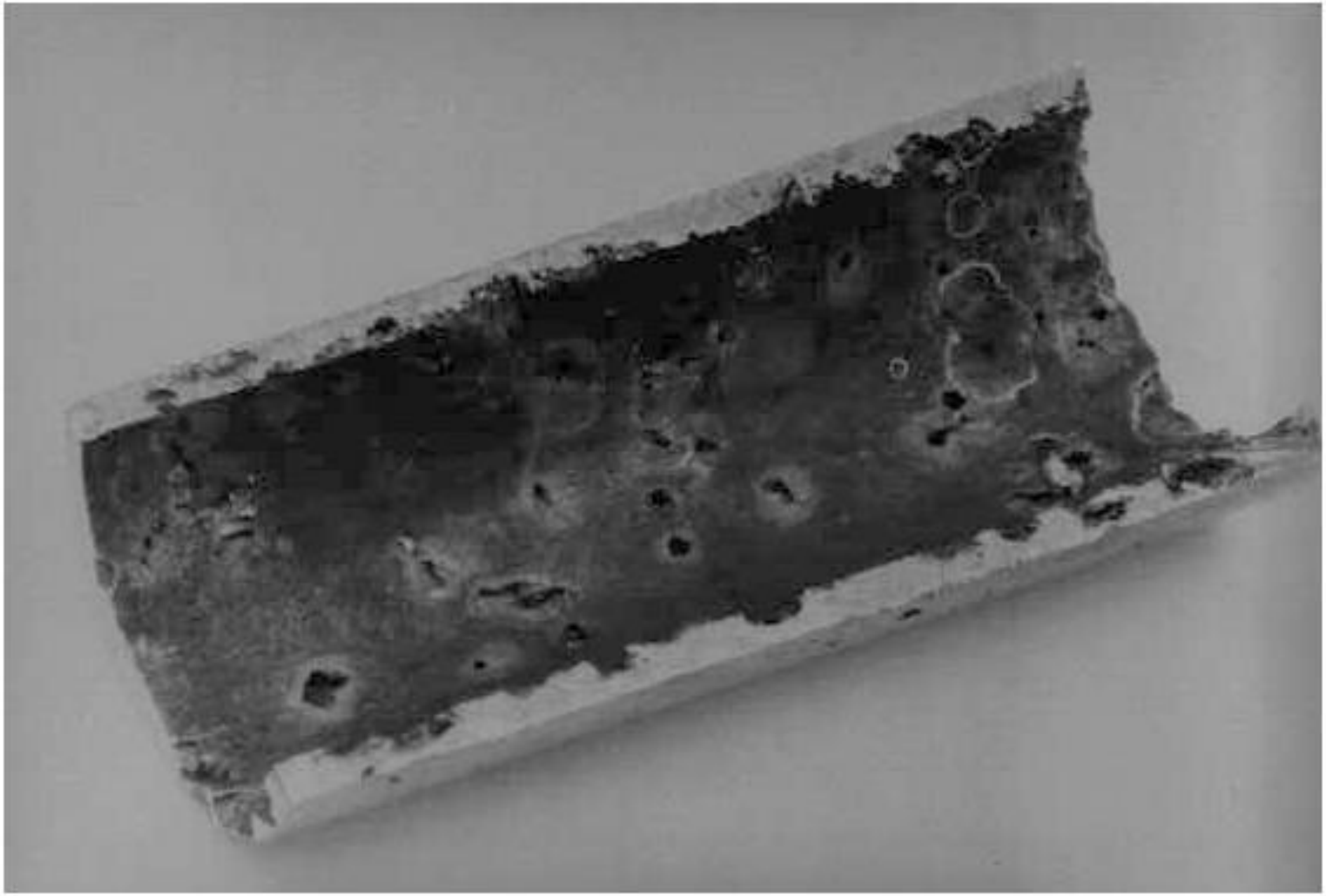
Limiting concentration for passivity in sulphuric acid for various stainless steels

Alloying elements Cr, Ni and Mo are beneficial as far as resistance in sulphuric acid is concerned

Pitting & crevice corrosion

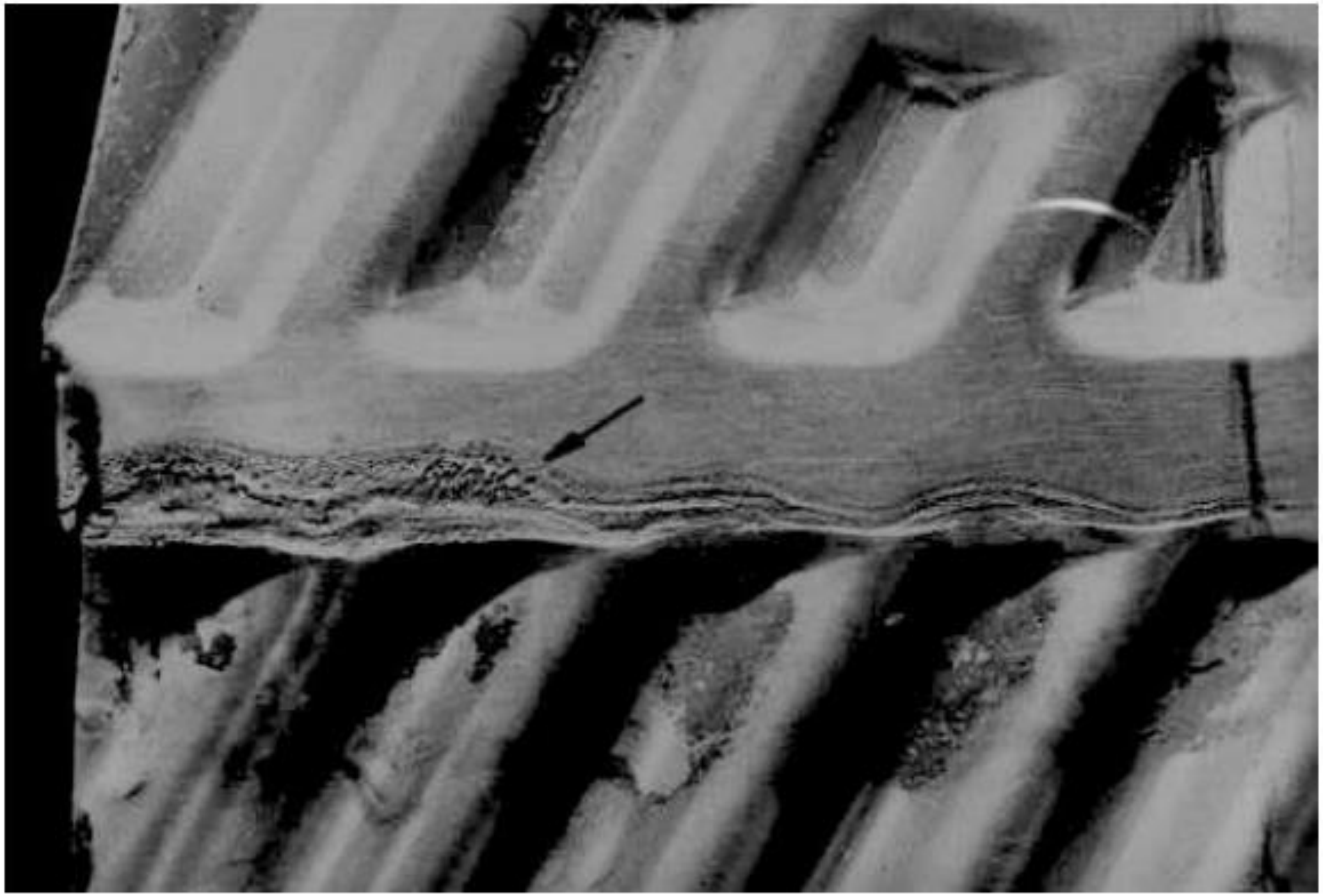
- Like all materials that rely on passive film for corrosion resistance, stainless steels are also susceptible to localized corrosion
- The protective passive film is never fully perfect and always contain microscopic defects.
- If halogen ions such as chlorides are present in the atmosphere (e.g. in seawater or sea shore constructions), they can locally break down the passive film and prevent their re-formation.
- This cause localized corrosion attack, whereby the damage propagates inwards while the majority of the surface remains mostly unaffected.

Pitting & crevice corrosion



Pitting corrosion on a tube of AISI 304 stainless steel in brackish water

Pitting & crevice corrosion



Crevice corrosion under a rubber washer in a heat exchanger used in brackish water

Pitting & crevice corrosion

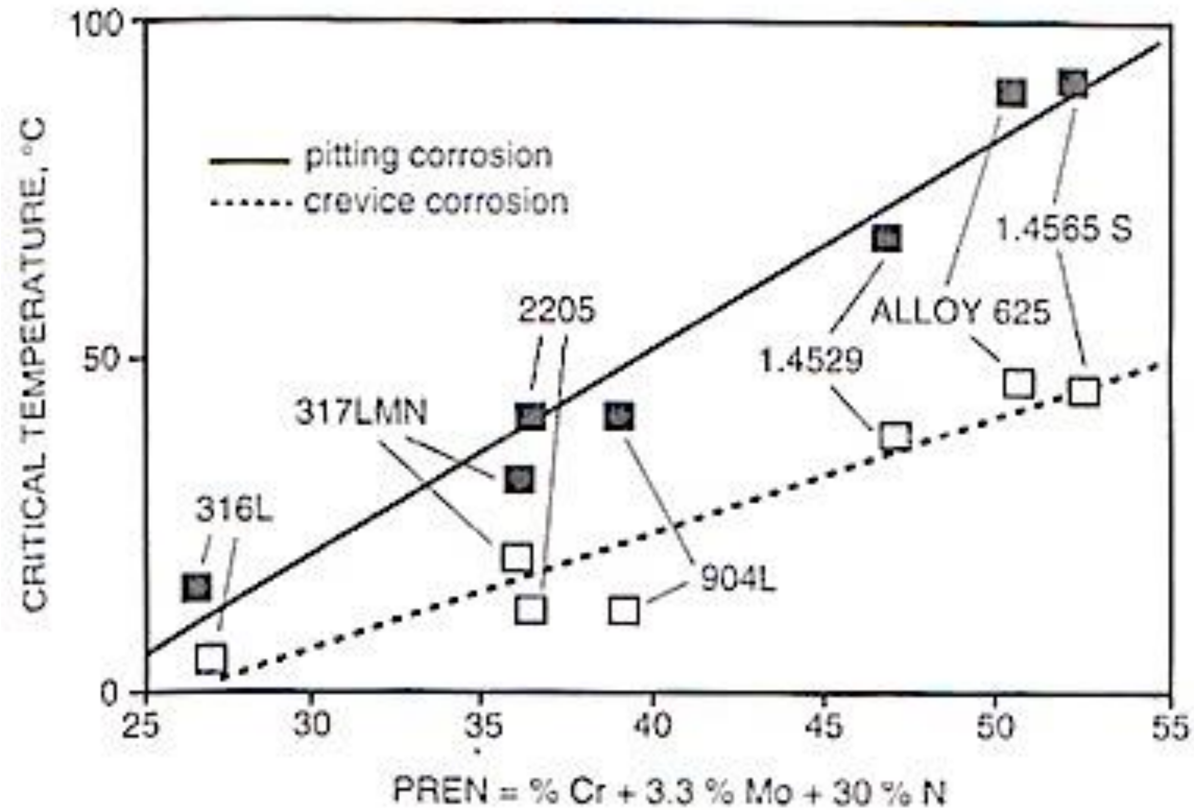
- The alloying elements chromium, molybdenum and nitrogen in stainless steel increase the resistance to both pitting and crevice corrosion.
- The quantity Pitting Resistance Equivalent (PRE) combines the effects of Cr, Mo and N in a stainless steel to resist pitting attack

$$PRE = \%Cr + 3.3 \times \%Mo + 16 \times \%N$$

- The higher the PRE value of a stainless steel, the more resistant it is against pitting corrosion.
- Steels for sea water applications must have a minimum Mo-content of 6 wt.%

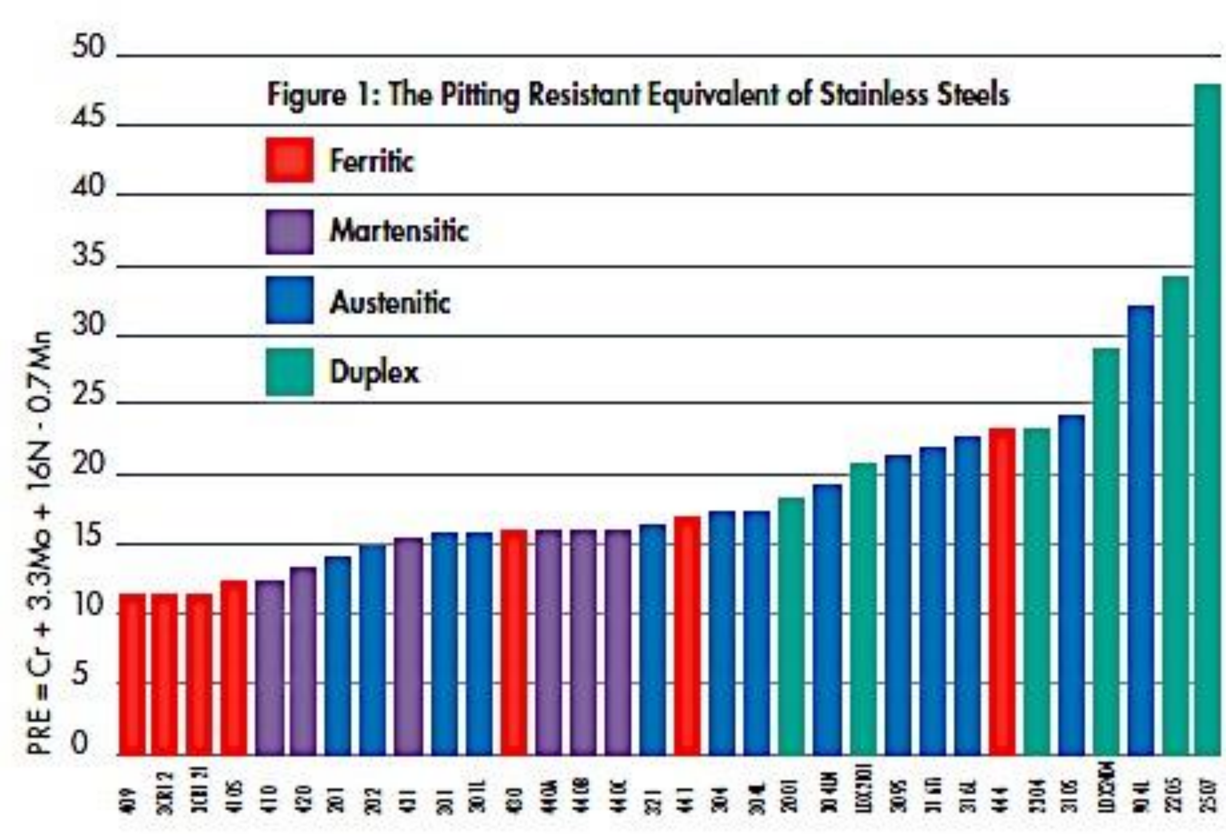
*Often a coefficient of 30 is used for nitrogen

Pitting & crevice corrosion



- Critical pitting and crevice corrosion temperatures are the lowest temperatures at which corrosion initiates
- Both these temperatures increase with increasing PRE

Pitting & crevice corrosion



Pitting resistance equivalent of different stainless steels