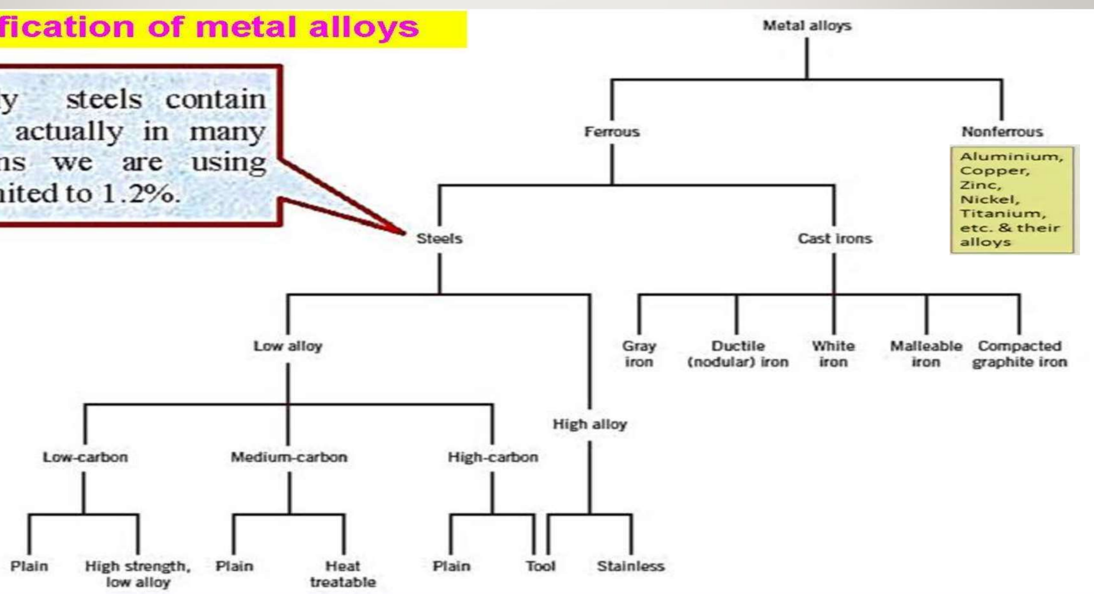
Steel

Classification of metal alloys

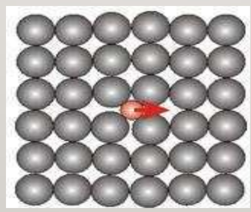
Technically steels contain 2.1% but actually in many applications we are using carbon limited to 1.2%.



Plain stands for only Fe-c with out any alloying element

Iron

- The Iron Age began about 3000 years ago and **continues till today**.
- Carbon forms an **interstitial solid solution** when added to **iron** to form **Steel** as the **atomic radius** of the carbon (0.071 nm) atom is **much less** than that for iron (0.124 nm).
- Use of iron and steel has changed drastically the human development.
- Iron posses **allotropy** - exist in two or more **different forms** in the **same** physical **state**.
  - ✓ T < 770°C : Ferrite (α-iron), Ferromagnetic, BCC crystal structure.
  - ✓ T = 770 - 912°C : β–iron, paramagnetic, BCC crystal structure.
  - ✓ T = 912 -1394°C : γ-iron (austenite), FCC crystal structure.
  - ✓ T = 1394-1538°C : δ-iron, BCC crystal structure.



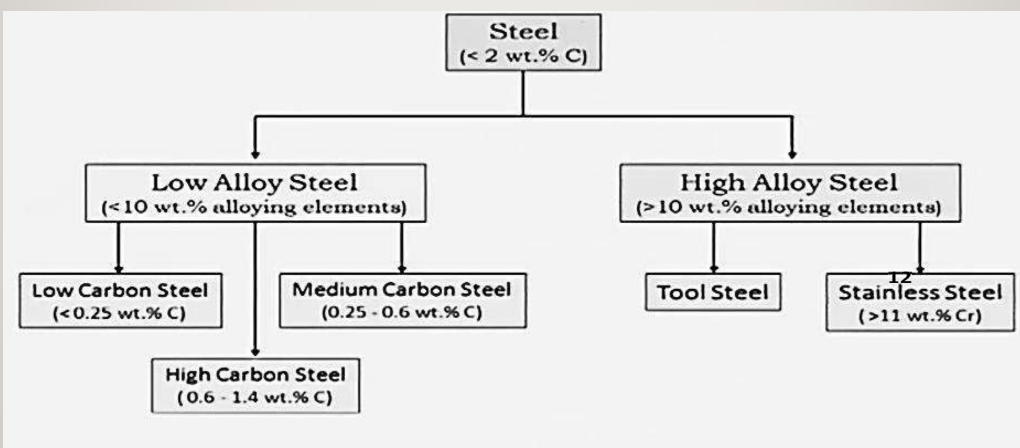
Interstitial impurity atom

WHAT DO YOU MEAN BY FERROMAGNETIC?

- **Ferromagnetism** is the basic mechanism by which certain materials (such as iron) form permanent magnets, or **are** attracted to magnets. In physics, several different types of magnetism **are** distinguished.

WHAT IS PARAMAGNETIC AND EXAMPLES?

- Paramagnetism refers to a property of certain materials that are weakly attracted to magnetic fields.



Low alloy steel is further divided into Plain carbon steel and Alloy steel of respective category.

As per **American Iron and Steel Institute** (AISI) definition for **Plain carbon steel:**

- ✓ When no minimum content is specified for alloying element (Cr, Co, Mo, Ni, Ti, W, V, Zr, etc.) to be added to obtain a desired effect.

OR

- ✓ When the specified minimum amount for copper (Cu) does not exceed 0.40 percent.

OR

- ✓ When the maximum content for any of the following elements does not exceed the percentages: Manganese (1.65), Silicon (0.60), Copper (0.60).

- Effects of increasing carbon content in steel are:
  - ✓ Increase in hardness & strength.
  - ✓ Decrease in weldability.
  - ✓ Decrease in ductility.
  - ✓ Decreased machinability (about 0.2 to 0.25 wt.% C provides the best machinability).

ALLOY STEELS

❑ Various elements like Cr, Mn, Ni, W, Mo etc are added to plain carbon steels to create alloy steels

Role of Alloying Elements

Element Added
- Segregation / phase separation
- Solid solution
  - Interstitial
  - Substitutional
- Compound (new crystal structure)

Plain Carbon Steel
- + Simplicity of heat treatment and lower cost
- – Low hardenability
- – Loss of hardness on tempering
- – Low corrosion and oxidation resistance
- – Low strength at high temperatures

Alloying elements
- ↑ hardenability
- Provide a fine distribution of alloy carbides during tempering
- ↑ resistance to softening on tempering
- ↑ corrosion and oxidation resistance
- ↑ strength at high temperatures
- Strengthen steels that cannot be quenched
- Make easier to obtain the properties throughout a larger section
- ↑ Elastic limit (no increase in toughness)

Low Carbon Steel

- Contain less than about 0.25 wt.% C (Mild steel).
- Relatively soft and weak.
- Outstanding ductility (25% EL) & toughness.
- Also, high machinability and weldability.
- Least expensive to produce.
- Tensile strength (415-550 MPa).

Low alloy steel:
- Contains alloys such as Cu, V, Ni & Mo up to 10 wt.%
- High strength & corrosion resistance than plain low carbon steel.
- Tensile strength up to 700 MPa.

Applications:
Beams, Channels, nuts, bolts, wires, tin cans, etc.

Medium Carbon Steel

- Contain 0.25 - 0.6 wt.% C.
- Stronger than low-C steels but of low ductility and toughness.
- Good wear resistance.
- Plain carbon steel (Tensile strength up to 850 MPa) & alloy steel (Tensile strength up to 1900 MPa)
- **Applications:** Railway wheels & tracks, gears, crankshafts, etc.

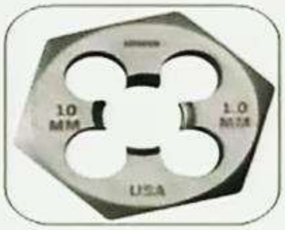
Rail wheels

Gears

Crankshaft

High Carbon Steel

- 0.6 - 1.4 wt. % C .
- Hardest, strongest and least ductile carbon steel.
- Can be alloyed with carbon and other metals to form very hard and wear resistance material (e.g. Cr, Ni, W, Mo and V).
- **Applications**: Cutting tools, embossing dies, saws, concrete drills, etc.



Die


Circular saw


Concrete drill

High Alloy Steel(>10 wt.% alloys) - Tool Steel

- ✓ Commonly used in drill bits & other rotating cutting tools.
- ✓ It can withstand higher temperatures without losing its hardness & toughness.
- ✓ **Example**
  - ❖ 18-4-1 HSS: 18% tungsten, 4% chromium, 1% vanadium with a carbon content of 0.6 - 0.7%.
  - ❖ Cobalt high speed steel – increased heat resistance
  - ❖ Molybdenum high speed steel – Mo increases hardness and wear resistance. Also cost effective replacement for tungsten in tool steels.

High Alloy Steel - Stainless Steel

- Highly resistant to corrosion in a variety of environment.
- Pre-dominant alloy: **Chromium (at least 11 wt.%).**
- **Example**: 18/8 stainless steel - 18% chromium and 8% nickel.
- **Applications:**
  - ✓ Cryogenic vessels.
  - ✓ Food processing equipment's.
  - ✓ Gas turbines parts.
  - ✓ High-temperature steam boilers.
  - ✓ Heat-treating furnaces.
  - ✓ Nuclear power generating units.

Cryogenic vessels are double walled cylindrical tanks with inner stainless steel and outer carbon steel sections painted with anti-corrosion primer and filled with an insulating material.

Effect of alloying elements on Steel

Or Role of major alloy elements

S.No.	Element	Effects
1.	Boron (B)	✓ Improves hardenability without the loss of machinability.
2.	Chromium (Cr)	✓ Improves oxidation (at high temperature) and corrosion resistance. ✓ Corrosion resistance may also be enhanced by Ni and Mo additions.
3.	Cobalt (Co) & Tungsten (W)	✓ Improves strength and hardness at elevated temperatures.
4.	Sulphur (S)	✓ Improves machinability when combined with manganese. ✓ Alone it increases brittleness & lowers impact strength and ductility.
5.	Manganese (Mn)	✓ Improves hardenability & wear resistance. ✓ Counteracts the brittleness caused by Sulphur.
6.	Molybdenum (Mo)	✓ Improves hardenability, toughness. ✓ Improves elevated-temperature strength, creep resistance.
7.	Nickel (Ni)	✓ Increases strength and hardness without sacrificing ductility and toughness.
8.	Vanadium	✓ Increases strength, hardness, wear resistance and resistance to shock impact at high temperature.
9.	Titanium	✓ Improves strength. ✓ Deoxidizes steels.

Relative effect on Steel

	Cr	Mn	Mo	Ni	Ti	W	V
Hardenability	++	++	++	+	++	++	+++
High temperature Strength	+		++	++	+	++	++
Ductility & Toughness		+		++			
Wear resistance	+		+		+	++	+
Promote fine grain size			+		++	+	+++
Corrosion resistance	++		+	+			

Hardness is a material property & is a resistance to penetration, scratching, etc.

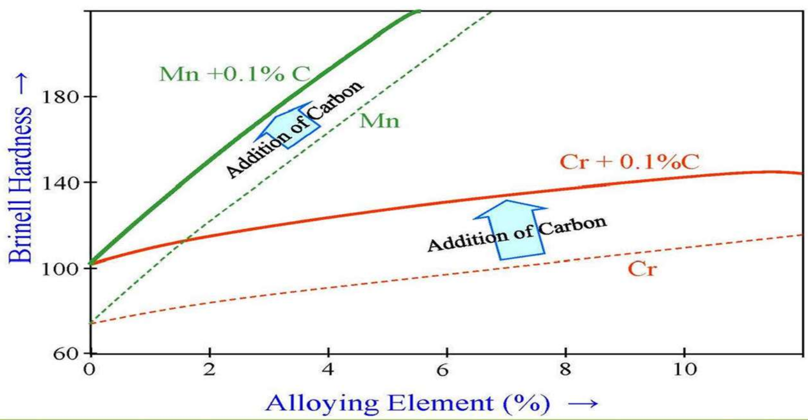
Hardenability is a way to indicate a **material's potential** to be hardened by heat treatment.

Alloy addition: why?

Why go for expensive alloy steel when such wide range of strength & toughness can be achieved in carbon / micro alloyed steel?

- Section size limitation: hardenability
- High strength / weight ratio
- Machinability
- Corrosion / oxidation resistance
- Magnetic properties (soft / hard)
- Creep resistance

Creep resistance is a term used in materials science that refers to a solid material's ability to resist "**creep**," which refers to the tendency of a material to slowly deform over a long period of exposure to high levels of stress.



Alloying elements increase hardenability but the major contribution to hardness comes from Carbon

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AISI –SAE Steel Specification

Series	Steel type
10xx	Plain carbon steel
11xx	Plain carbon steel (high S, low P)
12xx	Plain carbon steel (high S, high P)
13xx	Mn-Steel (Mn 1.75%)
23xx	Ni-Steel (Ni 3.00%)
25xx	Ni-Steel (Ni 5.00%)
31xx	Ni-Cr Steel (Ni 1.25%, Cr 0.60%)
33xx	Ni-Cr Steel (Ni 3.50%, Cr 1.50%)
40xx	Molybdenum steel (Mo 0.20 or 0.25)
41xx	Chrom – Moly steel (Cr 0.50, 0.80, or 0.95. Mo 0.12,0.20 or 0.30
43xx	No-Cr-Mo steel
44xx	Molybdenum 0.53
92xx	Silicon steel (Si 2.0%) ……etc.

These standard specifications given by different societies, and they developed different series of (Fe-c) alloys based on different compositions. For each type they given a standard series number…!

AISI (American Iron and Steel Institute)
SAE (Society of Automotive Engineering)
JIS ⇨Japanese Standard
DIN ⇨German Standard
TIS ⇨ Thai Standard

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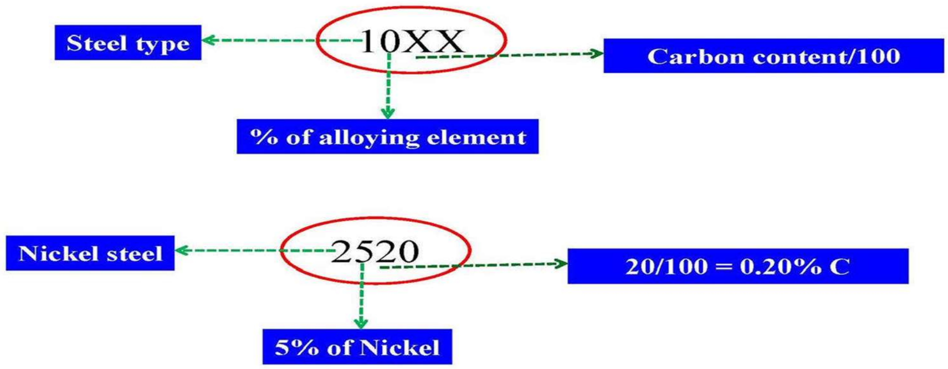
AISI –SAE Steel Specification



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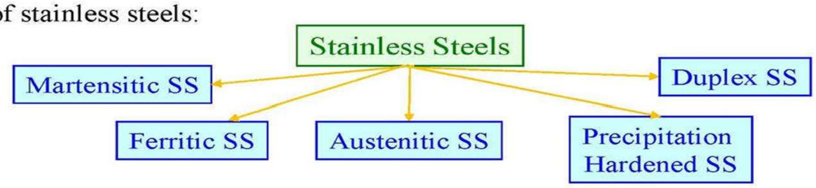
Stainless Steels

- Stainless Steels are a large group of special alloys developed primarily to withstand corrosion. These steels contain chromium in excess of 12% by weight which imparts "stainless" characteristics to iron alloys.
- Types of stainless steels:



- AISI Grades of stainless steels:

Series Designation	Groups
2xx	Chromium-Nickel-Manganese; Nonhardenable, Austenitic, Nonmagnetic
3xx	Chromium-Nickel; Nonhardenable, Austenitic, Nonmagnetic
4xx	Chromium; Hardenable, Martensitic, Magnetic
4xx	Chromium; Nonhardenable, Ferritic, Magnetic
5xx	Chromium; Low chromium; Heat-Resisting

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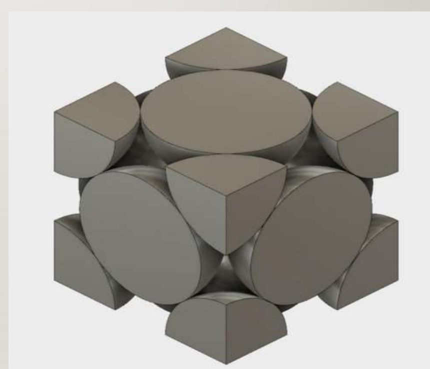
WHAT IS THE DIFFERENCE BETWEEN FERRITIC, AUSTENITIC & MARTENSITIC STAINLESS STEELS?

- **Ferritic Stainless Steel**
- Ferritic steels are made up of ferrite crystals, a form of iron which contains only a very small amount (up to 0.025%) of carbon. Ferrite absorbs such a small amount of carbon because of its body centred cubic crystal structure - one iron atom at each corner, and one in the middle. This central iron atom is what gives ferritic stainless steels their magnetic properties.
- Ferritic stainless steels are less widely-used due to their limited corrosion resistance and average strength and hardness.

WHAT IS THE DIFFERENCE BETWEEN FERRITIC, AUSTENITIC & MARTENSITIC STAINLESS STEELS?

Austenitic stainless steels contain austenite, a form of iron which can absorb more carbon than ferrite. Austenite is created by heating ferrite to 912 degrees C, at which point it transitions from a body centred cubic crystal structure to a face centred cubic crystal structure. Face centred cubic structures can absorb up to 2% carbon.

When austenite cools, it generally reverts back to its ferrite form, which makes austenite difficult to utilise at anything below the extreme temperatures of a smelting furnace. Austenite can be forced to retain its crystal structure at low temperatures with the inclusion of chemical additives, such as the nickel and manganese found in many austenitic stainless steels.



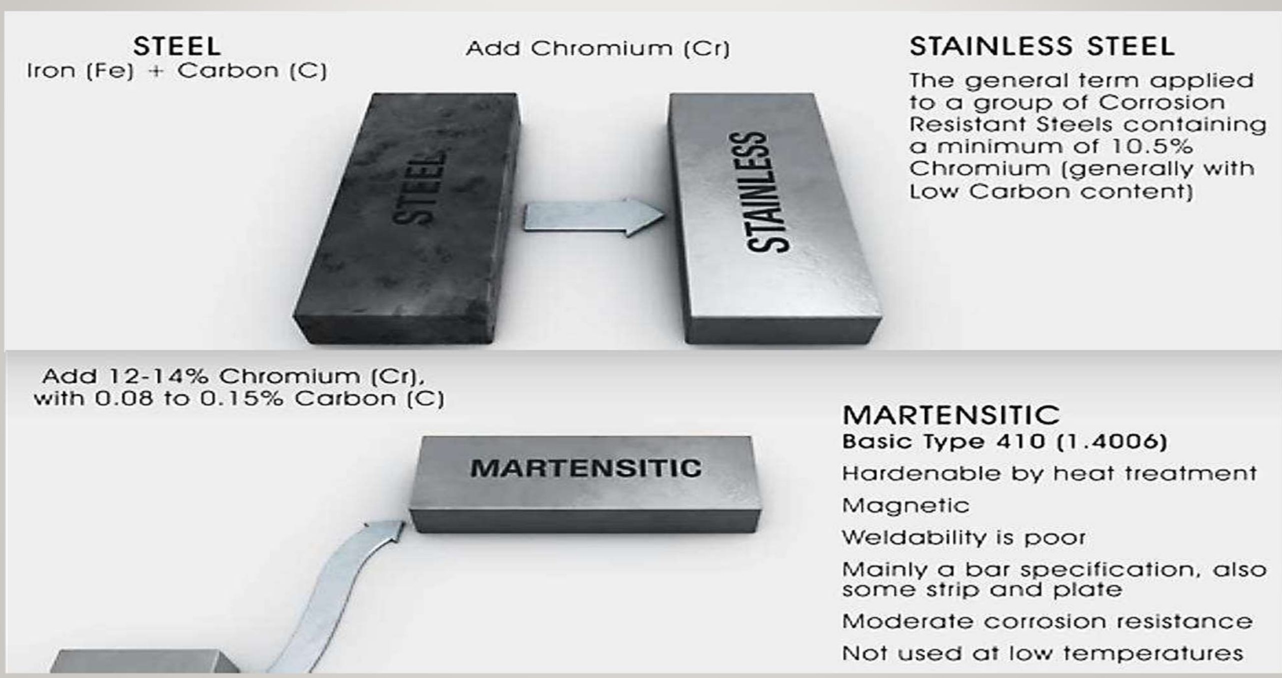
Face centred cubic crystalline structure of austenite.

Cementite

Cementite is a form of iron which contains even more carbon than ferrite and austenite. Cementite contains up to 6.67% carbon. Because of its increased carbon content, cementite is hard and brittle, and its presence is usually a byproduct, rather than by design. Cementite commonly occurs in steels when excess carbon, such as left-over carbon which cannot be absorbed into ferrite, must be used for the formation of crystals.

Pearlite

As iron cools, austenite crystals transition back into ferrite crystals, losing excess carbon which cannot be properly absorbed by the newly formed ferrite. The excess carbon creates patches of crystals with a mixture of low-carbon ferrite and leftover high-carbon cementite, and these mixed crystals are known as pearlite.



Add More Chromium (Cr)

FERRITIC

Basic Type 430 (1.4016)

Cannot be hardened by heat treatment

Always Magnetic

Moderate to good corrosion resistance

Weldability is reasonable in thinner sections but poor in thicker sections (over 2.5mm)

Good deep drawing properties

Generally a flat product specification

Not used at low temperatures

Add 18% Chromium (Cr)
& 8% Nickel (Ni)

AUSTENITIC

Basic Type 304 (1.4301)

Often called 18/8 Stainless

Non magnetic

Cannot be hardened by heat treatment, but hardenable by cold working, called work hardening

Excellent corrosion resistance

Easily fabricated and formed with good cold formability

Excellent weldability in all thicknesses

Suitable for both high and low temperatures (Cryogenics at -190°C to 870°C)

Add More Chromium (Cr), Nickel (Ni) & Other Elements

DUPLEX

e.g. 2205 (S31803)

Structure is mixture of Austenite and Ferrite

Magnetic

Excellent corrosion resistance, especially to localised pitting corrosion, crevice corrosion and stress corrosion cracking.

High Strength (Yield strength twice that of standard Austenitic grades)

Welding requires more control of parameters than standard austenitic grades

Often possible to use thinner material than would be needed in austentic grades

Add Chromium (Cr), Nickel (Ni), Manganese (Mn) & Copper (Cu)

PRECIPITATION HARDENING

e.g. 17/4PH (1.4542)

Very High Strength and Hardness up to 300°C – Achieved by Heat Treatment

Martensitic structure

Magnetic

Moderate Corrosion Resistance

Weldable

Tool Steel

- 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 temperatures (red-hardness).
- Tool steel are generally used in a heat-treated state.

AISI-SAE tool steel grades		
Defining property	AISI-SAE grade	Significant characteristics
Water-hardening	W	
Cold-working	O	Oil-hardening
	A	Air-hardening; medium alloy
	D	High carbon; high chromium
Shock resisting	S	
High speed	T	Tungsten base
	M	Molybdenum base
Hot-working	H	H1-H19: chromium base H20-H39: tungsten base H40-H59: molybdenum base
Plastic mold	P	
Special purpose	L	Low alloy
	F	Carbon tungsten

Plain high carbon steel that has been water quenched.

resist shocked at both low and high temperatures.
They also have high impact toughness **and relatively low abrasion resistance.**

designed to meet the needs of zinc die casting and the special **requirements of plastic injection molding dies.**

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High Speed Steel (HSS)

- HSS is a subset of tool steel, commonly used in tool bits and cutting tools. It is often used in power saw blades and drill bits.
- They are characterized by high carbon contents, sometimes up to 1.5%, and major additions of strong carbide forming elements such as chromium, molybdenum, tungsten and vanadium. Up to 12% Co is also included in some of the more complex grades.
- It can withstand higher temperatures without losing its temper (hardness) which allows it to cut faster than high carbon steel, hence the name.
- Other characteristics include high hardness, resistance to abrasion (excellent wear), an ability to hold a cutting edge, resistance to deformation at elevated temperatures (red-hardness).

High Strength Low Alloy (HSLA) steels

- A general description of HSLA steel is as that containing:
  1. low carbon (0.03–0.25%) content to obtain good toughness, formability, and weldability,
  2. one or more of the strong carbide-forming microalloying elements (MAEs) (e.g., V, Nb, or Ti),
  3. a group of solid solution strengthening elements (e.g., Mn up to 2.0% and Si), and
  4. one or more of the additional MAEs (e.g., Ca, Zr) and the rare earth elements, particularly Ce and La, for sulfide inclusion shape control and increasing toughness.
- In many other HSLA steels, small amounts of Ni, Cr, Cu, and particularly Mo are also present, which increase atmospheric corrosion resistance and hardenability.
- A very fine ferrite grain structure in the final product produced by a combination of controlled rolling and controlled cooling with an optimum utilization of microalloying additions, in HSLA steels, is an important factor in simultaneously increasing strength and toughness and decreasing the ductile–brittle transition temperature (to as low as -70°C).
- Carbides (NbC, VC, TiC), nitrides (TiN, NbN, AlN), and carbo-nitrides (e.g., V(C,N), Nb(C,N), (Nb,V) CN, (Nb,Ti) CN) are the dispersed second-phase particles that act as grain size refiners or dispersive strengthening phases in HSLA steels.
- HSL A steels are successfully used as ship, plate , bar, structural sections, and forged bar products, and find applications in several diverse fields such as oil and gas pipelines; in the automotive, agricultural, and pressure vessel industries, in offshore structures and platforms and in the constructions of crane, bridges , buildings, ship buildings, railroad , tank cars, and power transmission an d TV towers.

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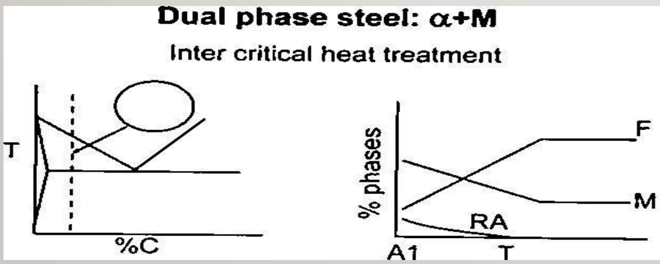
Microalloyed Steel

- Microalloyed steel → Contains small amounts (< 0.2%) of strong carbide forming elements such as niobium, vanadium, titanium, molybdenum, zirconium, boron, and rare earth metals → refines the grain microstructure (Grain size of ferrite ASTM 12-14) & facilitates precipitation hardening (by forming fine dispersion of alloy carbides).
- These steels have improved strength and excellent weldability compared to mild steel. In terms of performance and cost, these steels lie between carbon steel and low alloyed steel.
- Typical mechanical properties of Microalloyed steel are: Yield Strength → 400-500 Mpa, Tensile Strength → 600-650 Mpa, % Elongation → 20-22.
- Used in vehicles/transportation, tubular components, heavy equipment, rails, off-shore/platforms, bridges, suspension components, building structures etc.

Dual Phase Steels

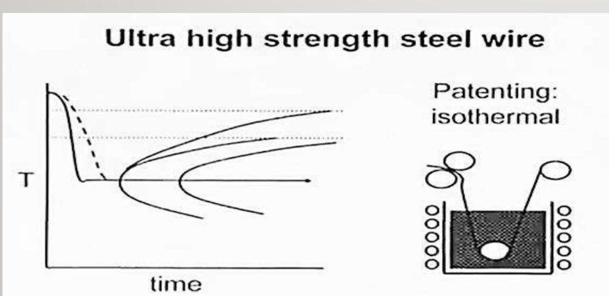
- Dual – Phase (DP) steels were developed in the mid-seventies in order to satisfy the increasing needs of automotive industry for new high strength steels, which combine significant weight reduction improved crash performance, while keeping the manufacturing costs at affordable levels.
- Duel-phase steels are characterized by a microstructure consisting of a fine dispersion of hard martensite particles in a continuous, soft, ductile ferrite matrix. The term 'dual-phase' refers to the presence of essentially two phases, ferrite and martensite, in the microstructure, although small amount of bainite, pearlite and retained austenite may also be present.
- Irrespective of the chemical composition of the alloy, the simplest way to obtain a dual phase ferritic-martensitic steel is intercritical annealing of a ferritic-pearlitic microstructure in the $\alpha+\gamma$ two phase field. Followed by a sufficiently rapid cooling to enable the austenite to martensite transformation.



Limitation: high cooling rate to convert γ to M: applicable to thin plates / sheets

Spring Steels

- Steels possessing high elastic limit, toughness and fatigue strength are suitable for manufacturing springs.
- Depending on the service conditions, a number of steels can be used for making springs.
- These desirable properties of spring can be achieved firstly by a higher carbon content or with suitable alloying elements, and secondly by heat treatment. Steel springs are used in hard, high strength condition. To attain these properties springs are hardened and tempered.
- High carbon steels are the cheapest among all the grades of spring steels. These steels are used in either hardened and tempered condition or in patented and cold-drawn conditions.



Fine lamellar pearlite: cold drawn to desired strength & diameter: 1200 – 3000MPa UTS: spring, suspension bridge, wire ropes

Maraging Steels

- Maraging Steels are ultrahigh strength steels based on Fe-Ni system.
- They derive their excellent properties due to combination of two solid state reactions:

MAR + AGEING

$\Rightarrow$ Meaning, Martensitic transformation in Fe-Ni system and its subsequent ageing.

- Fe-Ni martensite serves as an excellent host for a number of alloying elements which strengthen the steel on subsequent ageing.

Excellent Mechanical Properties	Good Processing and Fabrication Characteristics	Simple Heat Treatment
1. High strength and high strength-to-weight ratio. 2. High plane strain fracture toughness. 3. High notch toughness 4. Maintains high strength up to at least 350°C.	1. Very good Hot and cold formability. 2. Work-hardening rates are low. 3. Excellent weldability, either in the annealed or aged condition. 4. Good machinability.	1. No quenching required. Softened and solution treated by air cooling from 820-900°C. 2. Hardened and strengthened by ageing at 450-500°C. 3. No decarburization effects 4. Dimensional changes during age hardening are very small – possible to finish machine before hardening. 5. Can be surface hardened by nitriding.

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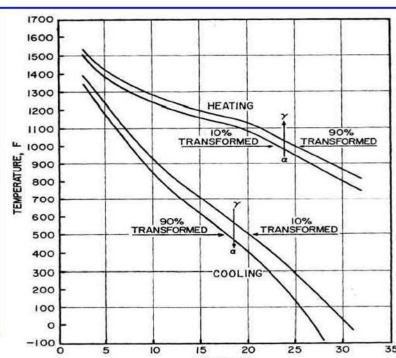
Maraging Steels : Martensitic Transformation

- Austenite (γ) $\leftrightarrow$ Martensite (α) transformation in Fe-Ni systems depend on Ni content
- Fe-Ni transformation diagram developed by John & Pumphrey
- Gilbert & Owen established that at least 18% Ni was essential to favour martensitic transformation in Fe-Ni system
- At lower concentration of Ni, because of higher temperature, thermodynamic conditions do not favour diffusion less transformation and α - ferrite is formed

- The nature of transformation, nevertheless, also depends on other alloying elements and interstitials.
- Blocky type of martensite has been found to occur over a wide range of Nickel (10-25%).
- In Maraging Steels, on solution treatment, the austenite transforms to blocky martensite having bcc crystal structure irrespective of cooling rate.
- **Microstructure produced by annealing 1 hr at 800^{0}C; 100% bcc phase (Figure a)**
- **Microstructure produced by Annealing 1 hr at 1240^{0}C; 100% bcc phase. (Figure b)**



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Fe-Ni transformation Diagram