ME 216 – Engineering Materials II

Chapter 8

Alloy Steels & Cast Irons

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- **Plain carbon steels** are with low carbon content (up to 1% **C**) and without alloying elements. They are the most economical and commonly used steels (up to 90% of steels produced).
- However, for specific applications, they do not comply with such requirements as follows:
  - **Hardenability**
  - **Softening on tempering**
  - **High/low temperature strength**
  - **Corrosion resistance**
  - **Special properties (such as ferromagnetism)**
- Therefore, **alloy steels** have been developed to provide such characteristics. Specific alloying elements are added to steels for imparting required characteristics. These steels become more expensive, and hence employed where plain carbon steels are inadequate.
- Alloy steels provide one or more of those properties. This is achieved by effect of alloying elements on iron-carbon (**Fe-C**) system, which can be in many ways. The way in which **Fe-C** system is influenced depends upon the nature of alloying element.

- Three most important equilibrium constituents of steel are **ferrite**, **austenite** and **cementite**.
- Alloying elements influence the properties of steels by altering the behavior of one or more of these phases in one or more of the following ways:

1. Altering **Fe-C** system by changing eutectoid temperature or eutectoid carbon content.
2. Dissolving in ferrite to increase strength.
3. Forming complex carbides (e.g. $\mathbf{Cr_{23}C_6}$) that are hard and brittle, thus increasing strength.
4. Forming an intermediate compound with iron (like **FeCr** or $\mathbf{Fe_2W_2}$). Such compounds may increase strength due to dispersion hardening.
5. Altering isothermal transformation diagram so that **martensite** could be formed by slower cooling, thereby increasing hardenability.
6. Reducing volume change during γ-α transformation, thus reducing dimensional changes.
7. Cleaning steel by combining with impurities (**V**, **Mn**, **Zn** combine with **S** to form **sulphides**)
8. Forming surface oxide film for corrosion protection (**Cr**, **Cu**, **Al**, **Si** provide such protection, **chromium oxide** gives the characteristic corrosion resistance to stainless steels).
9. Increasing creep resistance by dispersion of fine carbides (such as **MoC**).

Alteration of Iron-Carbon Diagram

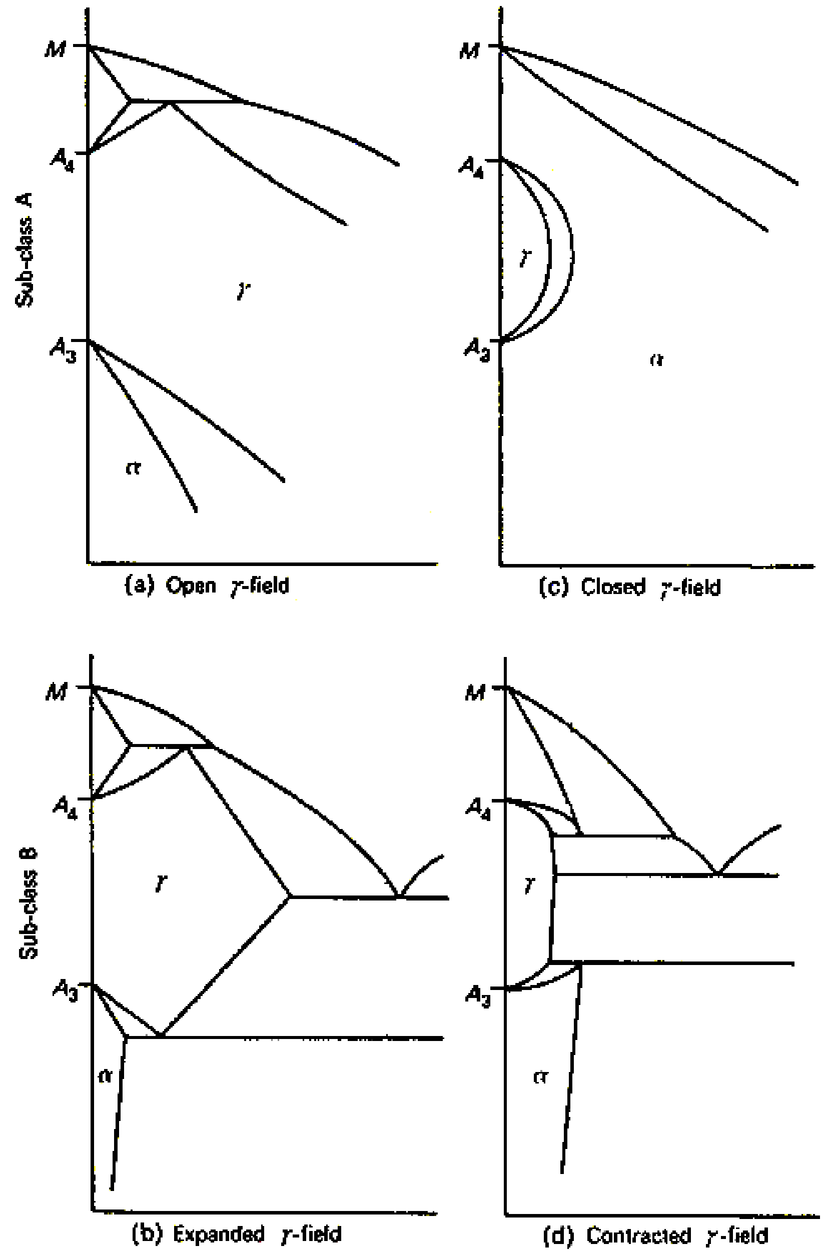
- Fe-C binary system falls into **four main classes**:

a) **Open γ-field:** **Ni**, **Mn**, **Co** with inert metals (**ruthenium**, **rhodium**, **palladium**, **osmium**, **iridium**, **platinum**) are in this class. **Ni** and **Mn** eliminate **α-phase** and replace it with **γ-phase**. Critical temperatures are depressed down to room temperature to obtain metastable austenite at room temperature (such as in austenitic stainless steels).

b) **Expanded γ-field:** **C** & **N** are the most important elements. **γ-field** is expanded (to degree by formation of compounds), and cementite is formed above 2% **C**. Expansion of **γ-field** by **C** & **N** underlies the whole of heat treatment of steels, by allowing the formation of austenite up to 2% **C** and 2.8% **N**.

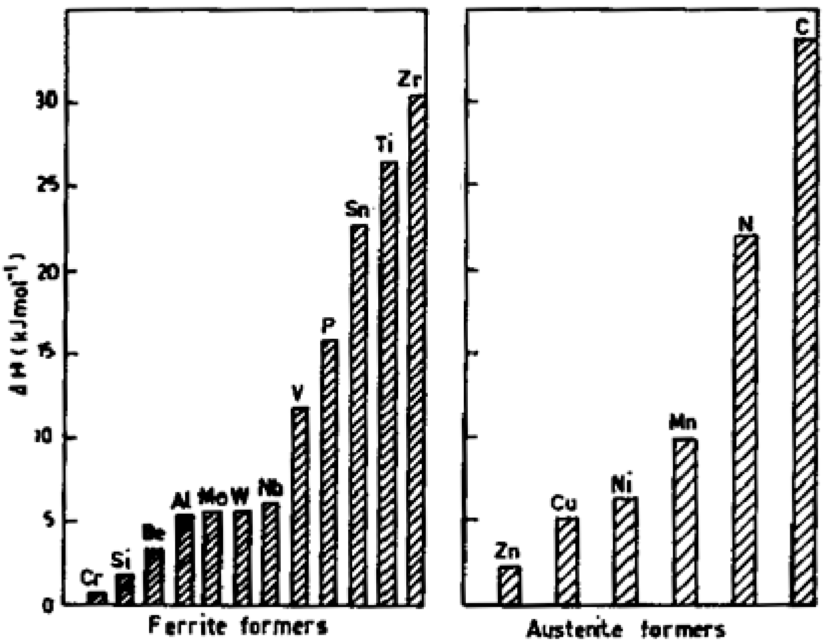
c) **Closed γ-field:** **Si**, **Al**, **Be**, **P** with strong carbide formers (**Ti**, **V**, **Mo**, **Cr**) restrict the formation of γ to very small area (**γ-loop**). They encourage the formation of α so that δ and α fields become continuous. Such alloys are not amenable to heat treatments involving γ → α phase transformation.

d) **Contracted γ-field:** **Boron** with carbide forming elements (**tantalum**, **niobium**, **zirconium**) cause contracting **γ-loop**, which is accompanied by compound formation.

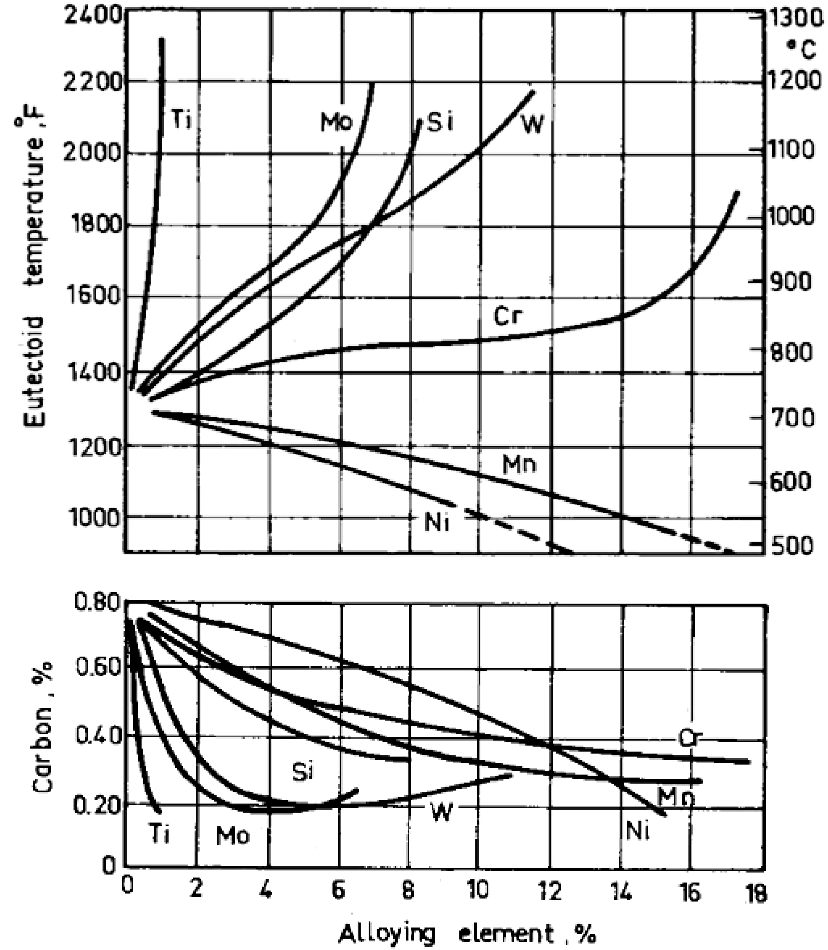


Alteration of Iron-Carbon Diagram

- So, alloying elements can alter diagram in two ways:
  1. **by expanding γ-field:** encouraging **formation of austenite** over wide composition & temperature range (these elements are called **γ-stabilisers**).
  2. **by contracting γ-field:** encouraging **formation of ferrite** over wide composition & temperature range (these elements are called **α-stabilisers**).



Influence of alloying elements as formers of α and γ



Changes in eutectoid temperature and eutectoid carbon composition

Distribution of Alloying Elements in Steel

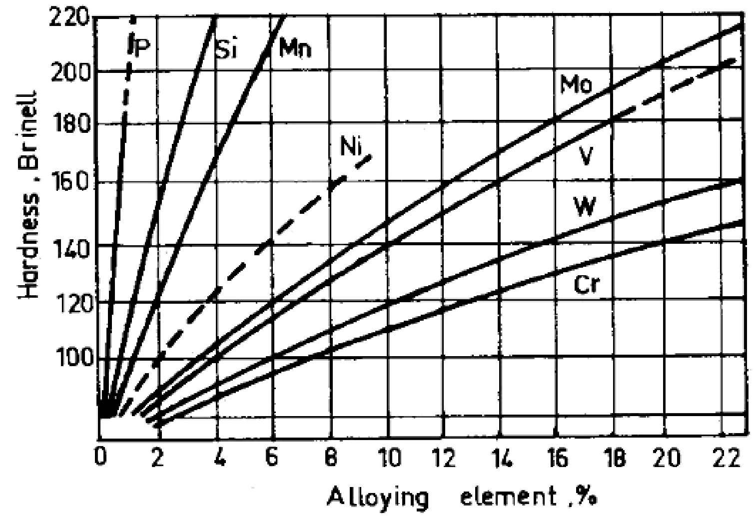
- For steels in which γ transforms to α and Fe_3C on slow cooling, alloying elements are categorized as follows:

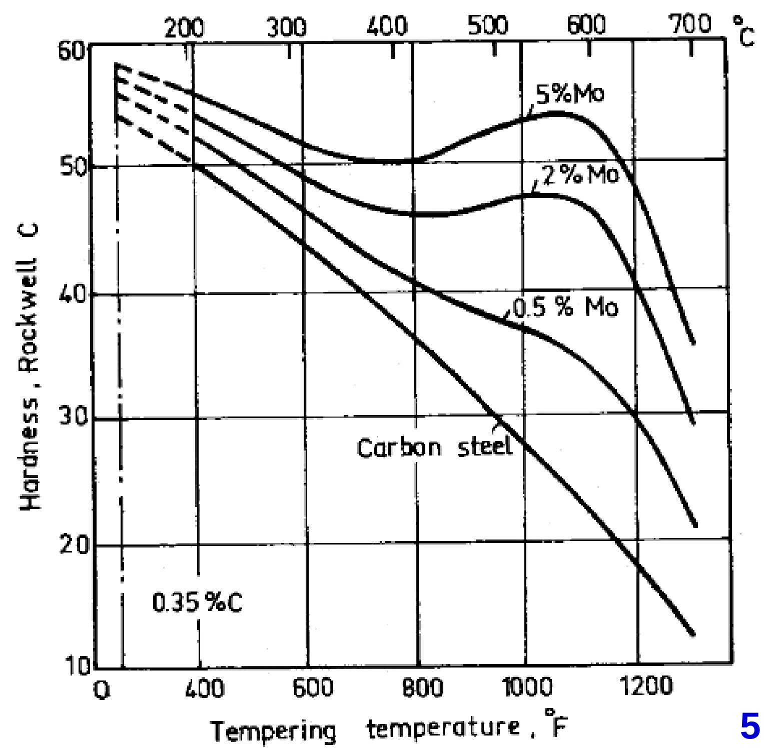
1. **Elements only dissolve in α:** Such elements (**Ni**, **P**, **Si**) do not form carbides, and only soluble in α. They increase strength of α although their overall contribution to strength is not significant since α is a weak phase in steels.

2. **Elements dissolve in α & form carbides:** Majority of elements (e.g. **Mo**) are carbide formers and soluble in α. They go into solid solution in Fe_3C and α at low concentrations. At high concentration, they form carbides, more stable than **Fe** carbide.

3. **Elements only form stable carbides:** Few elements fall in this category as carbide formers (e.g. **N** forming **carbonitrides**). In presence of strong nitride forming elements (**Ti**, **Al**), separate nitride phases may occur.

4. **Elements promote graphitization:** Such elements (**Si**, **Co**, **Ni**, **Al**) tend to form graphite, which decomposes carbides and reduces strength drastically. Thus, carbide formers are added in steels containing these elements to counter their effects.





- There are over 70,000 types of steels (more are being developed). In order to make their selection easier, a classification has been made **based on their composition and functions**:

STEELS

- **Plain Carbon Steels**
- **Tool Steels**
  - **Water Hardening (W)**
  - **Shock Resisting (S)**
  - **Cold Working (O, A, D)**
  - **Hot Working (H)**
  - **High Speed (M, T)**
  - **Special Purpose (L, F, P)**
  - **Special Cutting**
    - Stellites
    - Cemented Carbides
    - Ceramic Tools
- **Stainless Steels**
  - **Austenitic (200, 300)**
  - **Ferritic (405, 430, 446)**
  - **Martensitic (403, 410, 416, 420, 501, 502)**
  - **Precipitation Hardening**
- **High-Strength Low-Alloy (HSLA) Steels**
- **Maraging Steels**
- **Other Steels**
  - **Mn (13xx)**
  - **Ni (2xxx)**
  - **Ni-Cr (3xxx)**
  - **Mo (4xxx)**
    - Cr-Mo (40xx)
    - Cr-Ni-Mo (43xx)
    - Ni-Mo (46xx)
  - **Cr (5xxx)**
  - **Cr-V (6xxx)**
  - **W (7xxx)**
  - **Si (8xxx)**
  - **Super Alloys**

- Tool steels are very clean high quality special purpose steels, produced by electric processes making them very expensive. They are characterized by high strength, and are used in machine tools for cutting and forming.

- They are classified by **American Iron & Steel Institute (AISI)** according to quenching media (water, oil, etc.), alloy content (carbon tool steels, low alloy tool steels, etc.), their applications (hot-work steels, shock-resisting steels, etc.), and rated based on the following properties:
  - **Depth of hardening:** related to hardenabilty.
  - **Nondeforming properties:** describe the distortion obtained during hardening (quenching) from the hardening temperature.
  - **Toughness:** the ability to resist breaking (rather than the ability to absorb energy, as usually defined).
  - **Wear resistance:** the resistance to abrasion or to loss of dimensional tolerances.
  - **Red hardness:** the resistance to the softening effects of heat.
  - **Machinability:** the ability to be cut freely and produce a good finish.
  - **Resistance to decarburisation:** the ability not to lose carbon when heated above about 600 °C, as decarburisation softens the metal.

CLASS	TYPE	HARDENİNG (°C)	HARDENİNG MEDİUM	TEMPERİNG (°C)	HARDNESS (HRC)	DEPTH OF HARDENİNG
Water Hardening	W1	750-850	Brine/Water	150-350	65-50	Shallow
	W2	750-850	Brine/Water	150-350	65-50	Shallow
Shock Resisting	S1	900-1000	Oil	200-650	58-40	Medium
	S5	875-925	Oil	175-425	60-50	Medium
Cold Working	O1	800-820	Oil	150-250	62-57	Medium
	A2	925-1000	Air	175-550	62-57	Deep
	A4	820-875	Air	175-925	62-54	Deep
	D2	975-1075	Air	200-550	61-59	Deep
	D3	925-975	Oil	200-550	61-59	Deep
	D9	950-1000	Air	200-550	61-54	Deep
Hot Working	H11	1000-1025	Air	550-650	54-36	Deep
	H19	1100-1200	Oil/Air	550-700	59-40	Deep
	H21	1100-1200	Oil/Air	600-675	54-36	Deep
	H23	1200-1300	Oil/Air	650-820	47-30	Deep
	H26	1175-1250	Oil/Air/Salt	560-675	58-43	Deep
	H41	1100-1200	Oil/Air/Salt	560-650	60-50	Deep
High Speed (HSS)	T1	1250-1300	Oil/Air/Salt	550-600	65-60	Deep
	T4	1250-1300	Oil/Air/Salt	550-600	66-62	Deep
	T6	1275-1320	Oil/Air/Salt	550-600	65-60	Deep
	M1	1175-1225	Oil/Air/Salt	550-600	65-60	Deep
	M2	1200-1230	Oil/Air/Salt	550-600	65-60	Deep
	M6	1175-1200	Oil/Air/Salt	550-600	66-61	Deep
	M41	1100-1220	Oil/Air/5alt	550-600	70-65	Deep
Special Purpose	L2	800-850	Water	175-550	63-45	Medium
	L6	800-850	Oil	175-550	62-45	Medium
	F2	800-875	Brine/Water	150-250	66-62	Shallow
	P2	825-850	Oil	150-250	64-58	Shallow
	P20	820-875	Oil	425-600	37-28	Shallow

Water-Hardening Tool Steels (Type W)

- They are essentially plain carbon steels (with 0.6-1.4% **C**). They must be water quenched for high hardness, and subjected to considerable distortion. They have the best machinability, but poor resistance to heat. They are used for light cuts at low speeds on soft materials.

Shock-Resisting Tool Steels (Type S)

- These steels (0.45-0.65% **C**) are alloyed with **Si**, **Cr**, **W**, **Mo**. They are used for applications requiring toughness and ability to withstand repeated shock. Most of them are oil hardened.

Cold-Working Tool Steels (Type O, A, D)

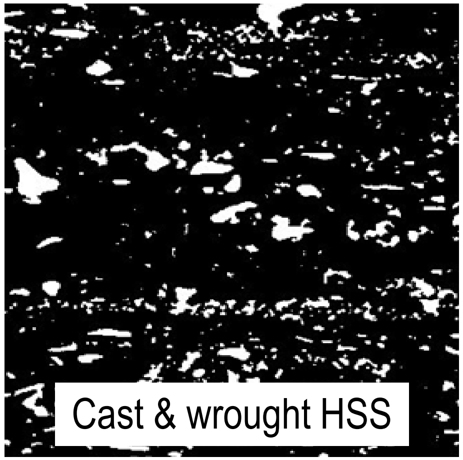
- The most important group of tool steels.
- Oil-hardening class (type O) contains **Mn**, **Cr**, **W**. They have good nondeforming properties (i.e. less likely to bend, sag, twist, distort, or crack during heat treatment).
- Air-hardening class (type A) contains 1% **C**, up to 3% **Mn**, up to 5% **Cr**, and 1% **Mo**. With increased alloy content (particularly **Mn** and **Mo**), they have increased hardenability.
- High-alloy class (type D) contains up to 2.25% **C** and 12% **Cr** (also containing **Mo**, **V**, **Co**). Combination of high **C** & high **Cr** gives excellent wear resistance and nondeforming during hardening, making these steels popular for blanking and piercing dies.

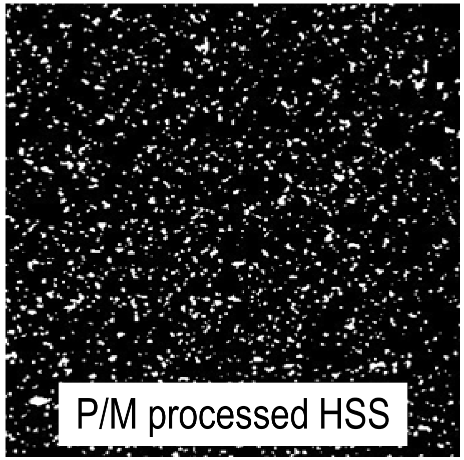
Hot-Working Tool Steels (Type H)

- They are subdivided into three groups:
  - **Cr**-base: with min. 3.25% **Cr** (H11-H19)
  - **W**-base: with min. 9% **W**, 2% **Cr** (H21-H26)
  - **Mo**-base: with 8% **Mo**, 4% **Cr** (H41)
- They have good toughness (due to low **C** content) and excellent red hardness (due to **Cr**, **Mo**, **W** at least 5% in total), fair wear resistance and machinability. Used for cases where tool is subjected to excessive heat (hot forging).

High Speed Steels – HSS (Type M, T)

- They are highly alloyed steels (large amount of **W** & **Mo** and **Cr**, **V**, **Co**) with 0.70-1.50% **C**.
- Mostly used for cutting tools, also in making extrusion dies, blanking/piercing dies, punches.
- Subdivided into two groups: **Mo**-base (type M) & **W**-base (type T)
- 18-4-1 (T1) is the most widely used (numerals denoting the content of **W**, **Cr**, **V**).
- They have good shock resistance and excellent red hardness (due to stable carbide formation after double-tempering, which can be improved by homogenous distribution of fine carbides).


Cast & wrought HSS


P/M processed HSS

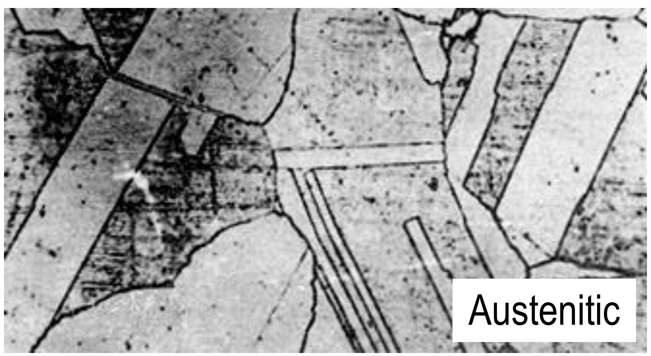
Special-Purpose Tool Steels (Type L, F, P)

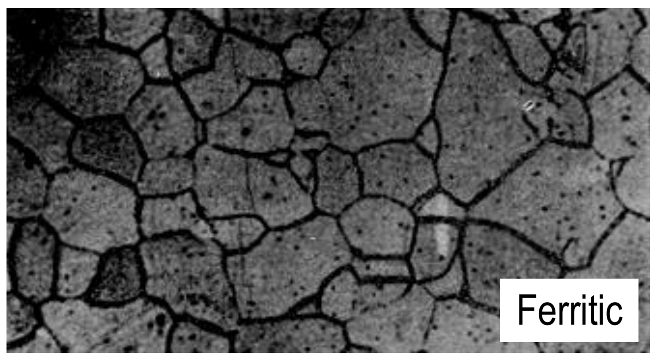
- Steels not falling into usual categories are designated as special-purpose tool steels.
- Low-alloy class (type L): containing **Cr** as the principal alloying element.
- Carbon-tungsten class (type F): shallow-hardening, water-quenching steels with high **C** & **W**.
- Mold steels (type P): containing **Cr** & **Ni** with **Mo** & **Al** as additives.

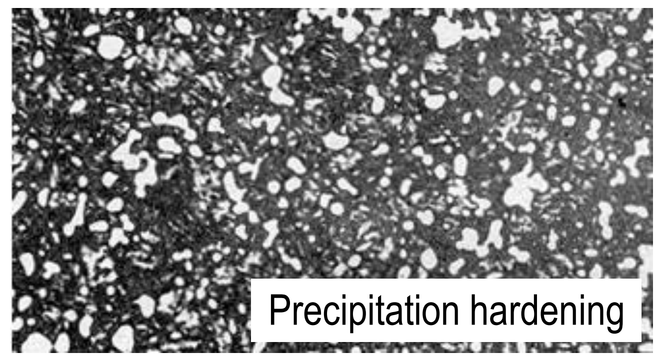
Special Cutting Materials

- **Stellites** are **Co**-**Cr**-**W** alloys (containing 25-35% **Cr**, 4-25% **W**, 1-3% **C**, remaining is **Co**). Very suitable for cutting applications due to their high hardness (40-60 HRC depending upon **W** & **C** content), high resistance to wear & corrosion, excellent red hardness.
- **Cemented carbides** (manufactured by P/M) are made of fine carbide particles of refractory metals (cemented with **Co**), forming structure of high hardness & compressive strength. They are classified as: **W**-carbide grades (used for machining cast irons & nonferrous materials), **Ti**/**Ta**-carbide grades (used for machining steels). They are coated with titanium nitride (to reduce coefficient of friction), which improves tool life considerably. The exceptional tool performance of sintered carbides result from high hardness (67 HRC) and high compressive strength combined with outstanding red hardness.
- **Ceramic tools** are manufactured from alumina (aluminum oxide). After consolidation into useful shape, they are sintered at 1700 °C. They are commonly used as disposable inserts available in many shapes. Alumina is very stable at metal cutting temperatures, and has very good resistance to wear. However, they are brittle, and must be properly mounted in suitable holders.

- They are very low carbon steels (with min. 10.5% **Cr**, while 501 & 502 steels have 4-6% **Cr**).
- They have superior resistance to corrosion and heat (which is proportional to **Cr** content). Corrosion resistance is provided by adherent film of chromium oxide on surface.
- They have considerably higher strength than plain carbon steels. Their high-temperature strength does not rely on carbides, but provided by **Cr** metal itself.
- They are classified into Series 300 (austenitic) and Series 400 (ferritic and martensitic). In addition, few of them are also available as Series 200 and Series 500.
- The microstucture of austenitic, ferritic, and precipitated stainless steels are shown below.







Austenitic Stainless Steels

- They are **Cr**-**Ni** (series 300) & **Cr**-**Ni**-**Mn** (series 200) steels (with min. 23% **Ni** & **Cr** in total).
- They are non-magnetic in annealed condition, and they do not harden by heat treatment. They can be hot worked easily, and also cold worked when allowance is made for their rapid work hardening. They may become slightly magnetic in cold worked condition.
- They are extremely shock resistant and difficult to machine. Among stainless steel group, they have the best high-temperature strength and resistance to scaling. They usually have better corrosion resistance than ferritic or martensitic stainless steels.

Ferritic Stainless Steels

- These are straight **Cr** steels (having about 14-27% **Cr**), and includes series of 405, 430, 446.
- Being magnetic, they are not hardened by heat treatment (only moderately hardened by cold working). They have maximum softeness, ductility and corrosion resistance in annealed condition. In annealed condition, they have 50% higher strength than plain carbon steels. They are superior to martensitic stainless steels in corrosion resistance and machinability.
- These steels are easily cold formed, and hence extensively used for deep drawing (such as vessels for chemical and food industries, and for architectural and automotive trims).

Martensitic Stainless Steels

- Also straight **Cr** steels (containing 11.5-18% **Cr**), with series of 403, 410, 416, 420, 501, 502.
- Series 410 & 416 are the most popular alloys, which are magnetic and can be cold worked easily (especially with low **C** content). They can be easily machined, have good toughness and corrosion resistance to weather and some chemicals. They attain their best corrosion resistance when hardened, but they are not as good as ferritic or austenitic stainless steels.

Precipitation Hardening Stainless Steels

- Developed during World War II, this group contains about 17% **Cr**, 7% **Ni** with **Mo** and others (**Cu**, **Al**, **Nb**, **P**).
- These steels are supplied in solution annealed condition, and after forming they are aged to attain an increase in hardness and strength due to precipitation.

High-Strength Low-Alloy (HSLA) Steels

- Developed to replace plain carbon steels, they contain up to 0.2% **C** with **Nb**, **V**, **Ti**, **Al**.
- They provide high strength due to extremely fine grain size. Their strength is improved without heat treatment, due to pinning action of fine dispersion of intermetallic compounds which slows down the grain growth and yields very small grains.
- Being inherently anisotropic (directionally sensitive), they are generally available in sheet or strip form. Grades of improved formability (developed primarily for automotive and construction industry) are 2-3 times stronger than plain carbon steels.

Maraging Steels

- Extremely high strengths due to martensitic transformation followed by aging (**mar-aging**). Aging of martensite produces fine dispersion of intermetallic precipitates, which imparts ultra-high strength. The martensite formed is soft and tough (rather than hard brittle martensite of conventional low alloy steels). This ductile martensite has low work hardening rate and can be cold worked to a high degree.
- There are two grades: 18% **Ni** grade (additions of **Co** & **Mo** with small amounts of **Ti** & **Al**) and 20-25% **Ni** grade (additions of **Ti**, **Al**, **Nb**).

Manganese Steels (13xx series)

- They are tough, hard and strong (fine grained grades attain unusual toughness & strength). These steels are used for gears, spline shafts. With moderate additions of **V**, they are used for large forgings to be air cooled. Steels with more than 10% **Mn** remain austenitic after slow cooling. **Hadfield steels** (containing about 12% **Mn**) can undergo severe service conditions of abrasion and wear.

Nickel Steels (2xxx series)

- Characterized by their strength consistent with toughness, plasticity and fatigue resistance. Suitable for high-strength structural applications (large forgings). 3.5% **Ni** grade is used for carburising of automotive parts. 5% **Ni** grade is used for heavy duty applications due to their increased toughness.

Nickel-Chromium Steels (3xxx series)

- Containing **Ni** & **Cr** with ratio of **2.5:1**, they are tough and wear resistant. Low-**C** grades are used for worm gear, piston. For heavy duty cases (aircraft parts), 3.5% **Ni** & 1.5% **Cr** is used. Usually, they are replaced by tripple-alloy steels (87xx and 88xx series) due to lower cost.

Molybdenum Steels (4xxx series)

- Exhibit good hardenability and high-temp strength. Low-**C** grades are used for transmission gear, spline shaft. High-**C** grades are suitable for automotive coil and leaf spring. **Cr-Mo** grades have good deep hardening with ductility and weldability, thus used for pressure vessels and aircraft parts. **Ni-Mo** grades exhibit good toughness with resistance to wear and fatigue, and used for bearings, gears and shafts.

Chromium Steels (5xxx series)

- Containing 0.15-0.64% **C** and 0.7-1.15% **Cr**, they are wear resistant steels. Medium-**C** grades are oil hardening, and used for springs and axles. High-**C** High-**Cr** grades are hard and wear resistant, and extensively employed for ball and roller bearings.

Vanadium Steels (6xxx series)

- Characterized by hardenability and strength on air cooling. **Cr-V** grades are used for heavy locomotive and machinery forgings. Low-**C** **Cr-V** grades are used in case-hardened condition for manufacture of pins and crankshaft. Medium-**C** **Cr-V** grades have good toughness and strength, and used for axles and springs. High-**C** **Cr-V** grades with high hardness and wear resistance are used for bearings and tools.

Tungsten Steels (7xxx series)

- Similar characteristics with **Mo** steels, more expensive. Due to their higher cost, they are not extensively used in engineering applications, instead used as alloying element for tool steels.

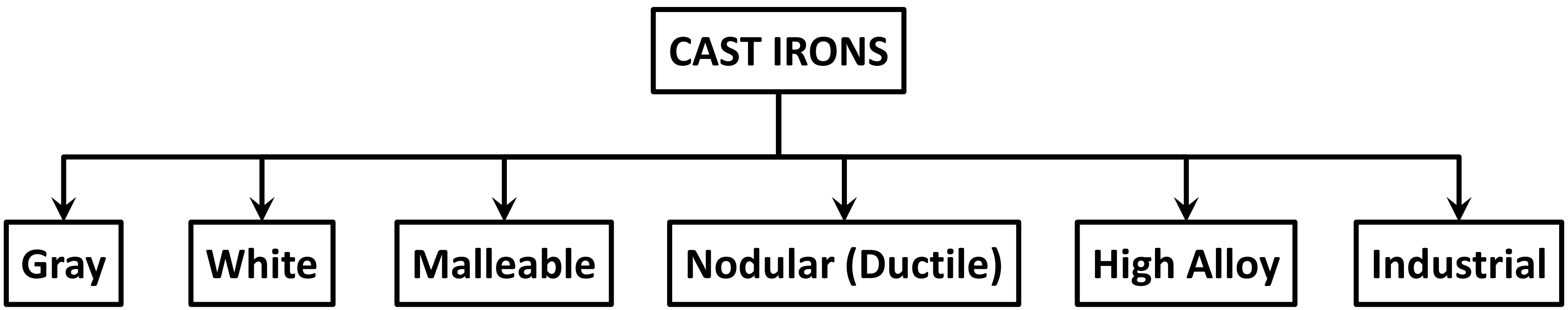
Silicon Steels (8xxx series)

- **Navy steel** (1-2% **Si**) is used for structural applications requiring high yield strength. **Hadfield Si steel** (0.01% **C**, 3% **Si**) has excellent magnetic properties for use in cores and poles of electrical machinery.

Super Alloys

- Alloys of **Ni**, **Co**, **Fe** (which is the cheapest). Developed for high-temperature applications.

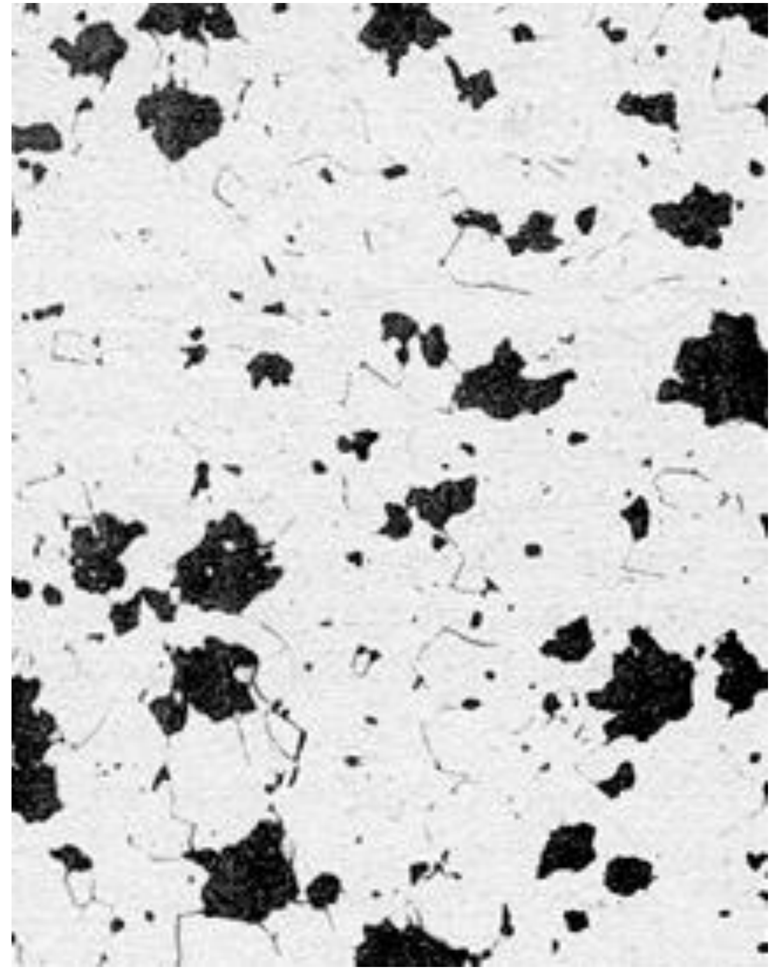
- Commercial cast irons contain 2-4% **C** with additions of **Si**, **Mn**, **S**, **P**.
- Maximum solubility of **C** in **Fe** is about 2%. Extra **C** in cast iron is present as super-saturated solid solution which precipitates out as either graphite (in various forms) or iron carbide.
- Thereby, cast irons are classified **according to type of precipitated carbon**:



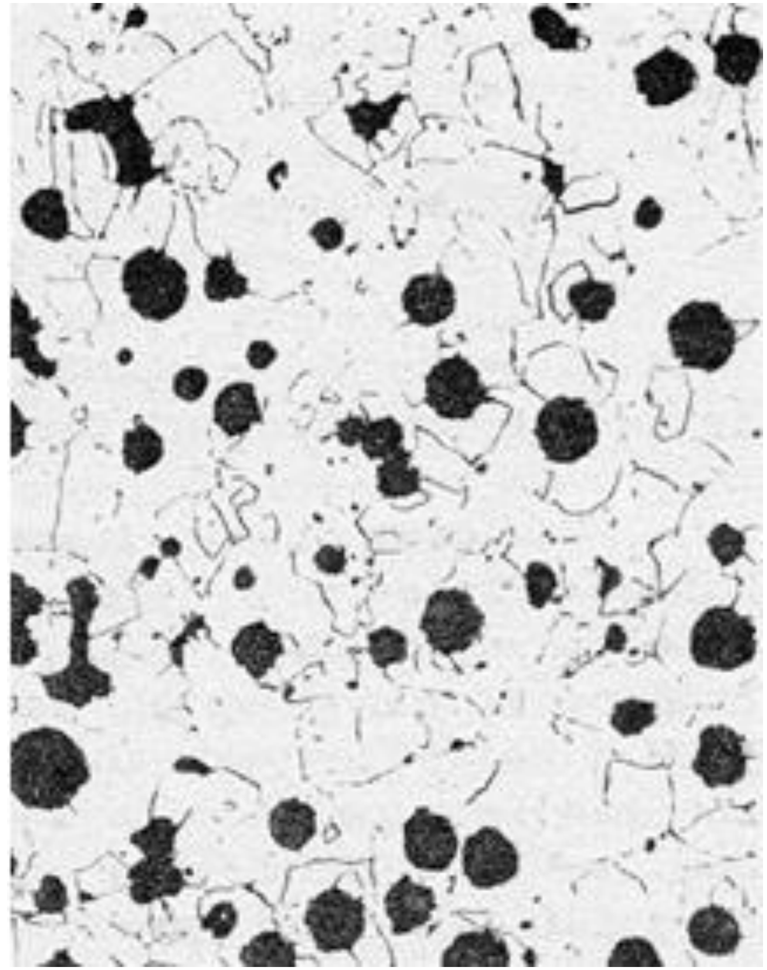
- It contains more than 1% **Si** and 1.7-3.5% **C**.
- Addition of **Si** enhances graphitization of **C** (**graphite as flakes**). Freshly fractured surface has grayish color, which gives its name.
- Compared to steel, it has lower modulus of elasticity and lower tensile strength with almost no ductility. It is low-melting iron (easily castable into complex shapes).
- It can withstand higher temperatures than steel without warping or oxidizing, and thus used for **furnace doors** due to this characteristic.
- Graphite network provides good corrosion resistance and good vibration damping, making it one of the most widely used alloys of iron.
- It is used for **furnace doors**, **guards and frames**, **housings**, **cylinder liners**, and **camshafts**.

- It contains most of iron as **iron carbide**.
- It has whitish appearance on fracture surface, and thus termed "white cast iron".
- It is very hard, abrasion resistant, and brittle material having pearlite grains. It is not machinable or weldable.
- It can be produced from gray or malleable cast iron by very fast cooling (**chilling**) process which suppresses precipitation of graphite.
- It is used for applications where wear resistance is important (such as **liners for concrete mixers**, **ball mills**, **drawing dies**, and **extrusion nozzles**).

- It contains **graphite as nodules** as result of two-stage heat treatment, which gives tempered carbon nodules.
- It may have ferritic, pearlitic, or even martensitic matrix (depending upon heat treatment).
- Yield strength and ductility are the same as soft steel.
- Tempered nodules act as lubricants during machining, making it very machinable.
- It has been widely used for **automotive, agricultural, and railroad equipments**.



- It has **graphite as tiny balls or spheroids**.
- In fact, it is a special type of gray cast iron, having tensile strength with increased ductility.
- Ductility is increased by inoculation by addition of small amounts of **Mg** (in the form of **Ni-Mg** alloy), which causes **graphite to take spherical (nodular) shape**, thus increasing the ductility.
- The matrix can be ferritic, pearlitic, martensitic, or even austenitic (depending upon alloying elements).
- It has similar properties to steel, but cheaper. It is machinable, and produces good finish.
- It is usually used where toughness and high strength are required (e.g. **fluid conducting applications**, **agricultural machinery parts**).



High-Alloy Irons

- Ductile, gray, or white irons (containing more than 3% alloying additions).
- They have significantly different properties than other cast irons, and produced by special foundries for specific purposes.
- For instance, nickel resist (with 15% **Ni**) is used for corrosion resistance while nickel hard is employed for wear resistance.

Industrial (Pure) Iron

- This iron is more corrosion resistant than its alloys, with unusually high ductility. On the other hand, tensile strength is much less than steel.
- Iron powder is pressed and sintered in molds to produce small parts of various structural shapes, requiring low strength.