Metallurgy

Metallurgy is the technology of extracting metals from their ores and adapting them for use and the science or study of the behavior, structure, properties, and composition of metals that leads to development of alloy properties.

Branches of metallurgy:

1. Extractive metallurgy, which is freeing the metal atoms from a combined state.
2. Physical metallurgy, which is the study of properties and composition of metals.
3. Powder metallurgy, which is the technology of producing useful metal shapes from metallic powder (P/M)

Definitions

- ***The physical world is composed of matter and energy. Matter is defined as anything that occupies space***

- *Matter is anything occupies space & composed of atoms*
- ***Energy is the ability to do work***

- ***Einstein's discoveries leading to this atomic age revealed that matter and energy are related. A small amount of matter releases a tremendous amount of energy under certain conditions.***

Definitions cont.

- ✖*An element* ***is*** *Matter composed of a single kind of atoms.*
- ✖*A compound is composed of two or more elements combined chemically.*
- ✖*A mixture is two or more elements or compounds physically combined in the same way in which two fine powders are mixed together*
- ✖*The molecule is defined as the smallest particle of any substance that can exist free and still exhibit all the chemical properties of that substance. A molecule can consist of one or more atoms*

Definitions cont.

Iron: pure iron or contains less than .02 wt % carbon.

Steel: iron + (contains $0.02 < \text{carbon} < 2.0$ wt %)

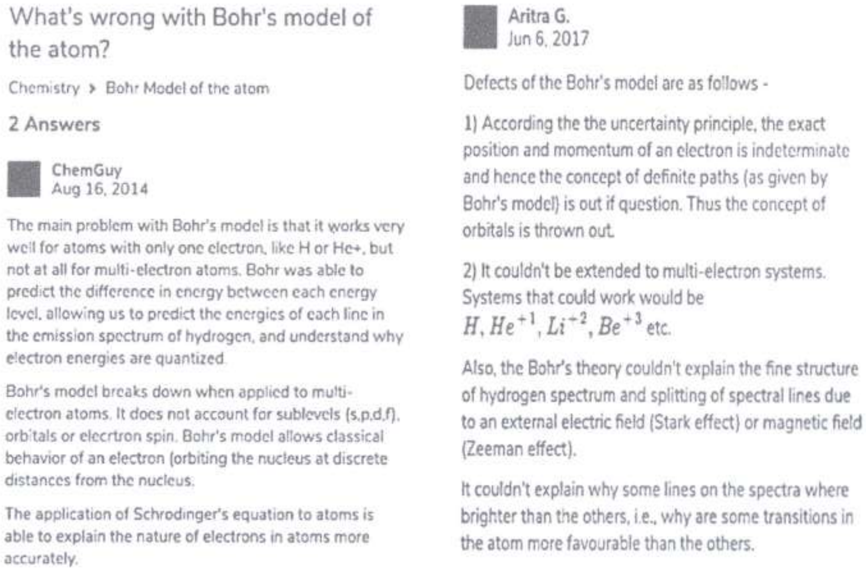
Cast Iron: Iron + (contains $2.0 < \text{carbon} < 6.69$ wt %)

Ferrous alloys: iron based alloys

Non-ferrous alloys: non iron based alloys

Plain carbon steel: contains only residual concentrations of impurities other than carbon and a little Mn.

Alloy steel: when more alloying elements are intentionally added in specific concentrations



What's wrong with Bohr's model of the atom?

Chemistry > Bohr Model of the atom

2 Answers

ChemGuy
Aug 16, 2014

The main problem with Bohr's model is that it works very well for atoms with only one electron, like H or He+, but not at all for multi-electron atoms. Bohr was able to predict the difference in energy between each energy level, allowing us to predict the energies of each line in the emission spectrum of hydrogen, and understand why electron energies are quantized.

Bohr's model breaks down when applied to multi-electron atoms. It does not account for sublevels (s,p,d,f), orbitals or elecrtron spin. Bohr's model allows classical behavior of an electron (orbiting the nucleus at discrete distances from the nucleus.

The application of Schrodinger's equation to atoms is able to explain the nature of electrons in atoms more accurately.

Aritra G.
Jun 6, 2017

Defects of the Bohr's model are as follows -

1) According the the uncertainty principle, the exact position and momentum of an electron is indeterminate and hence the concept of definite paths (as given by Bohr's model) is out if question. Thus the concept of orbitals is thrown out.

2) It couldn't be extended to multi-electron systems. Systems that could work would be $H, He^{+1}, Li^{+2}, Be^{+3}$ etc.

Also, the Bohr's theory couldn't explain the fine structure of hydrogen spectrum and splitting of spectral lines due to an external electric field (Stark effect) or magnetic field (Zeeman effect).

It couldn't explain why some lines on the spectra where brighter than the others, i.e., why are some transitions in the atom more favourable than the others.

Wave-mechanical model

ELECTRON ENERGY STATES

Electrons...

- **have discrete** energy states
- **tend to occupy lowest available energy state.**

POSITION*: *PROBABILITY DISTRIBUTION

OCCUPIRD ENERGY STATE (CONFIGURATION)*: *ACCORDING TO QUANTUM NUBERS & ENERGY STATE

QUANTUM NUMBERS:

1. ***PRINCIPAL NUMBER***
2. ***SECONDARY NUMBER***
3. ***MAGNETIC NUMBER***
4. ***SPIN NUMBER***

STABLE ELECTRON CONFIGURATIONS

Stable electron configurations...

- have complete s and p subshells
- tend to be unreactive.

Z	Element	Configuration
2	He	$1s^2$
10	Ne	$1s^2 2s^2 2p^6$
18	Ar	$1s^2 2s^2 2p^6 3s^2 3p^6$
36	Kr	$1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} 4s^2 4p^6$

SURVEY OF ELEMENTS

- Most elements: Electron configuration not stable.

Element	Atomic #	Electron configuration
Hydrogen	1	$1s^1$
Helium	2	$1s^2$ (stable)
Lithium	3	$1s^22s^1$
Beryllium	4	$1s^22s^2$
Boron	5	$1s^22s^22p^1$
Carbon	6	$1s^22s^22p^2$
...		...
Neon	10	$1s^22s^22p^6$ (stable)
Sodium	11	$1s^22s^22p^63s^1$
Magnesium	12	$1s^22s^22p^63s^2$
Aluminum	13	$1s^22s^22p^63s^23p^1$
...		...
Argon	18	$1s^22s^22p^63s^23p^6$ (stable)
...	...	...
Krypton	36	$1s^22s^22p^63s^23p^63d^{10}4s^24p^6$ (stable)

- Why? Valence (outer) shell usually not filled completely.

Atomic Bonds

Types of bonds:

- **Primary bonds**
  - *-Metallic*
  - *-Ionic*
  - *-Covalent*
- **Secondary bonds**

Secondary bonds are **bonds** of a different kind to the primary ones. They are weaker in nature and are broadly classified as Van der Waal's forces and hydrogen **bonds**. These **bonds** are due to atomic or molecular dipoles, both permanent and temporary. ... For example, water molecule is made of one oxygen and two hydrogen atoms

London forces are **intermolecular forces** of attraction holding molecules together. They are one of the *vander waal's forces* but are the only **force** present in materials that don't have polar dipole molecules . **e.g**,among the noble gases like Ne & Ar

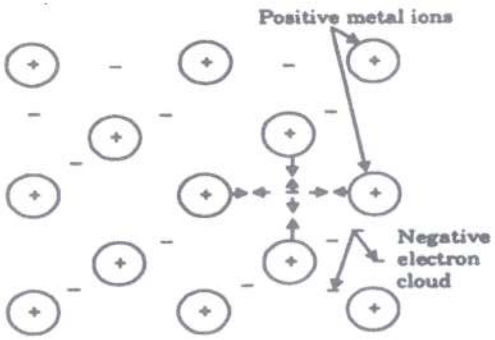
- **Mixed bonds**

- **Primary bond for metals and their alloys**

METALLIC BONDING

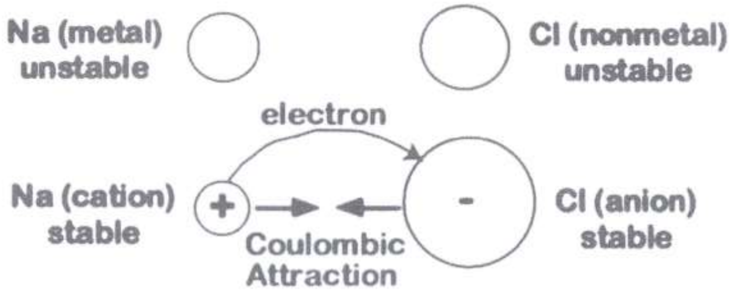
The cohesion of a metallic crystal is due to the attraction of the positive nuclei and the valence electrons passing between them. A metallic bond thus conceived can exist only between a large aggregate of metallic atoms and must therefore, be non-directional. The high electrical conductivity of metals is given by the free electrons moving freely in an electric field

- **Arises from a sea of** donated valence electrons **(1, 2, or 3 from each atom).**



IONIC BONDING

- **Occurs between + and - ions.**
- **Requires** electron transfer
- **Large difference in electronegativity required.**
- **Example: NaCl**



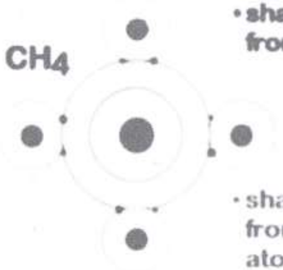
COVALENT BONDING

- **Requires** shared electrons
- **Example: CH4**

C: has 4 valence e, needs 4 more

H: has 1 valence e, needs 1 more

Electronegativities are comparable.

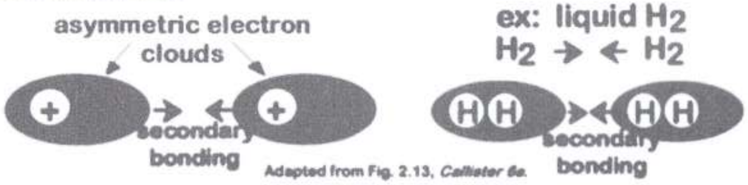


- **shared electrons from carbon atom**
- shared electrons from hydrogen atoms

SECONDARY BONDING

Arises from interaction between dipoles

- **Fluctuating dipoles**



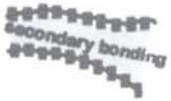
Adapted from Fig. 2.13, *Callister 6e.*

- **Permanent dipoles-molecule induced**

-general case:

-ex: liquid HCl

-ex: polymer



SUMMARY: BONDING

Type	Bond Energy	Comments
Ionic	Large!	Nondirectional (ceramics)
Covalent	Variable large-Diamond small-Bismuth	Directional semiconductors, ceramics polymer chains)
Metallic	Variable large-Tungsten small-Mercury	Nondirectional (metals)
Secondary	smallest	Directional inter-chain (polymer) inter-molecular

Mixed bonds

There are many substances in which bonding between atoms does not occur as one of the primary or secondary types of ideal bonding mentioned above but, rather, as a mixture of these bonds.

Quartz, glass or silica are the substances in which mixed *ionic & covalent* bonding occurs.

Ionic and metallic bonding produces many structural defects in the lattice of materials. It is found that there is a continuous change in bonding character in a series of alloys of metals such as copper-zinc.

Crystal structure

METALLIC CRYSTALS

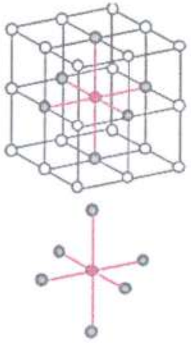
1. SIMPLE CUBIC CRYSTAL STRUCTURE
2. BODY CENTERED CUBIC CRYSTAL STRUCTURE (BCC)
3. FACE CENTERED CUBIC STRUCTURE (FCC)
4. HEXAGONAL CLOSE-PACKED CRYSTAL STRUCTURE (HCP)
5. TRICLINIC
6. MONOCLINIC
7. ORTHORHOMBIC
8. RHOMBOHEDRAL
9. TETRAGONAL
    - Simple
    - Body centered tetragonal (BCT)

SIMPLE CUBIC STRUCTURE (SC)

- Rare due to poor packing (only Po has this structure)
- Close-packed directions are cube edges.

(Courtesy P.M. Anderson)

- Coordination # = 6
  (# nearest neighbors)

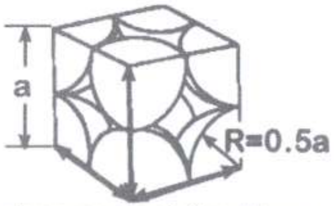


ATOMIC PACKING FACTOR

$$\text{APF} = \frac{\text{Volume of atoms in unit cell*}}{\text{Volume of unit cell}}$$

*assume hard spheres

- APF for a simple cubic structure = 0.52



close-packed directions
contains 8 x 1/8 =
1 atom/unit cell

$$\text{APF} = \frac{\underbrace{1}_{\frac{\text{atoms}}{\text{unit cell}}}\ \underbrace{\frac{4}{3}\pi(0.5a)^3}_{\frac{\text{volume}}{\text{atom}}}}{\underbrace{a^3}_{\frac{\text{volume}}{\text{unit cell}}}}$$

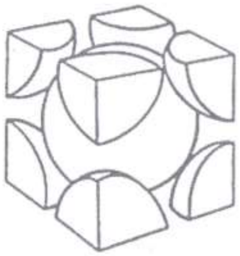
BODY CENTERED CUBIC STRUCTURE (BCC)

- Close packed directions are cube diagonals.

--Note: All atoms are identical; the center atom is shaded differently only for ease of viewing.

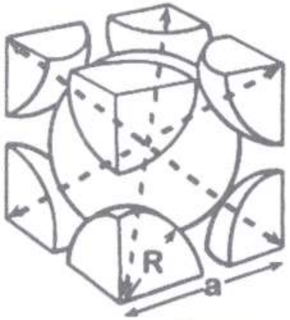
(Courtesy P.M. Anderson)

- Coordination # = 8



ATOMIC PACKING FACTOR: BCC

- APF for a body-centered cubic structure = 0.68



Close-packed directions:
length = 4R
$= \sqrt{3}\,a$

Unit cell contains:
1 + 8 x 1/8
= 2 atoms/unit cell

$$\text{APF} = \frac{\underbrace{2}_{\frac{\text{atoms}}{\text{unit cell}}}\ \underbrace{\frac{4}{3}\pi(\sqrt{3}a/4)^3}_{\frac{\text{volume}}{\text{atom}}}}{\underbrace{a^3}_{\frac{\text{volume}}{\text{unit cell}}}}$$

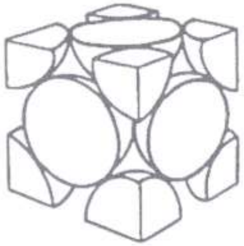
FACE CENTERED CUBIC STRUCTURE (FCC)

- Close packed directions are face diagonals.

--Note: All atoms are identical; the face-centered atoms are shaded differently only for ease of viewing.

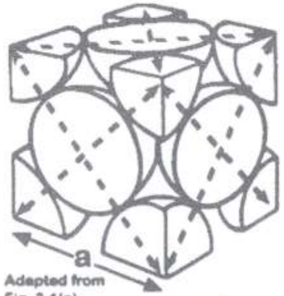
- Coordination # = 12

(Courtesy P.M. Anderson)



ATOMIC PACKING FACTOR: FCC

- APF for a body-centered cubic structure = 0.74



Adapted from Fig. 3.1(a), *Callister 6e.*

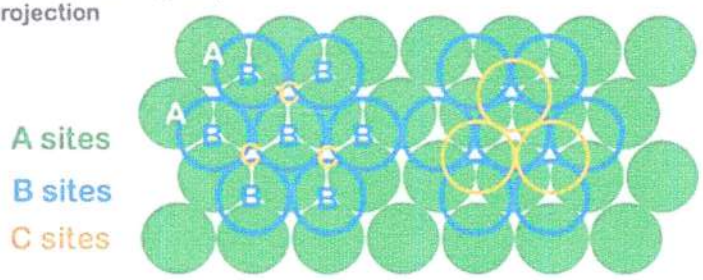
Close-packed directions:
length = 4R
= $\sqrt{2}$ a

Unit cell contains:
6 x 1/2 + 8 x 1/8
= 4 atoms/unit cell

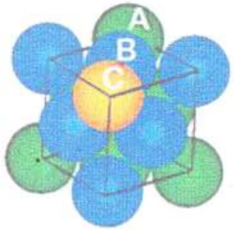
$$\text{APF} = \frac{\underset{\uparrow\ \frac{\text{atoms}}{\text{unit cell}}}{4}\ \underset{\uparrow\ \frac{\text{volume}}{\text{atom}}}{\frac{4}{3}\pi(\sqrt{2}a/4)^3}}{\underset{\uparrow\ \frac{\text{volume}}{\text{unit cell}}}{a^3}}$$

FCC STACKING SEQUENCE

- ABCABC... Stacking Sequence
- 2D Projection

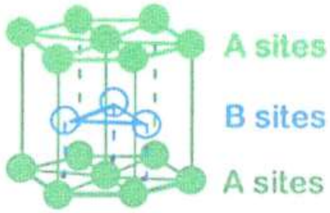


- FCC Unit Cell



HEXAGONAL CLOSE-PACKED STRUCTURE (HCP)

- ABAB... Stacking Sequence
- 3D Projection
- 2D Projection



- Coordination # = 12
- APF = 0.74

Microsturucture

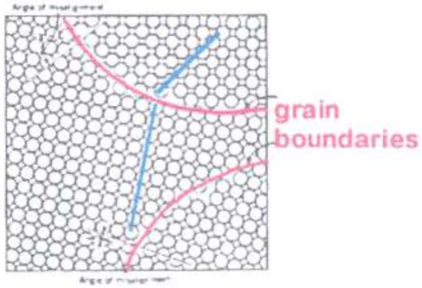
AREA DEFECTS: GRAIN BOUNDARIES

Grain boundaries:

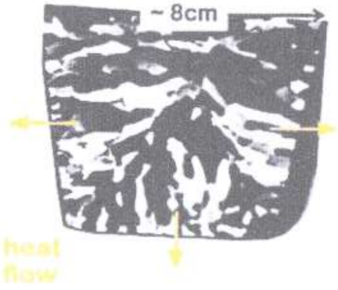
- are boundaries between crystals.
- are produced by the solidification process, for example.
- have a change in crystal orientation across them.
- impede dislocation motion.

In the grain: atoms of the same direction and same energy

Schematic



Metal Ingot



Grain size

- ***Mean linear intercept method***
- ***ASTM Method***
  $N = 2^{n-1}$
- N = 1- 5 coarse grained structure
- N = 5 – 8 Fine grained structure
- 70% falls in the range

The mean linear intercept method (Heyn method)

The mean linear intercept method (m.l.i.) is probably the widely used measurement method of grain size, particularly in metallurgical research. It is sometimes referred to as the Heyn intercept method. The m.l.i. is measured from a linear traverse by counting the number of grains which intercept a linear traverse length. If the L is the length of the intersecting line, N is the number of grains on this line, and m is the magnification thus the average diameter of the grain d can be determined by:

$$m.l.i. = d = L/(N*m) \ldots\ldots\ldots(4)$$

Cont.

- When counting the number of intercepts or grains, the following should be taken into consideration:
- If the line touches the grain boundaries, the number of grains is considered to be as N=0.5 (Figure 9).
- If the line passes through a triple point of grain boundaries, the number of grains is considered to be as N=1.5(Figure 10).
- If the line starts before or goes after the grain, the number of grains is estimated as ½ or ¼...etc (Figure 11).
- Select a suitable microscope magnification So that the number of grains that intercept the measuring line is not less than 30 and not more than 100.
- To get a representative grain size value, a total number of intercepts should be about 500.

Figure 9. The line touches the Grain Boundaries

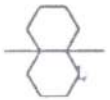


Figure 10. The line touches a triple point of Grain Boundaries

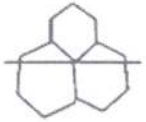
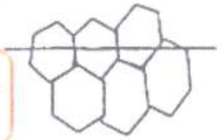


Figure 11. The line starts before or goes after the grain



It must be noted that the real grain size is greater than the measured on using the above formula because the intersection line passes through the chords of the grains and rarely through the centers of grains. Based on that, it must be appreciated that the m.l.i. diameter (d) is less than the average diameter of grains comprising the microstructure (D) which in turn less than the maximum grain diameter because (Dm). The relationship between d, D, and Dm depend on the grain shape assumed. By assuming a reasonable shapes for real grains and obtaining a mean linear intercept of rotation:

$$D = 1.75 * d \quad \text{.....................} (5)$$

Also, assuming Dm to be circumscribed sphere of rotation:

$$Dm = 1.86 * d \quad \text{.........................} (6)$$

It is also possible to relate ASTM grain size numbers to values of the *m.l.i.* as shown in Table 1. The relationship is a geometric progression in which each value of *m.l.i.* is smaller than its predecessor by a factor of 1/√2, d the table may be extended to larger or smaller grain sizes

The ASTM comparative chart method

In this method, the standard chart against which the microstructure is compared comprises either photomicrographs (mesh of irregular shapes) or idealized hexagonal (mesh of regular shapes) networks based on the number of grains intersecting unit area of the plane of polish. The comparison is made by holding the standard grain size chart alongside the image of the material grain projected on ground glass screen attached to a photomicrograph. If such projection equipment is not available, the comparison can be made using a transparent ASTM network which is overlaid on the photomicrograph of the required grain structure at the proper magnification.

In this method, the grain index number is an arbitrary experimental number with reference to the mean number of grains per square inch at a magnification of 100x. Thus, if the ASTM grain size number is *N*, this is related to the number of grains *n* per square inch area and magnification 100x by:

$$n = 2^{(N-1)} \quad \text{..} (1)$$

or

$$N = 1 + (\log n)/(\log 2) \quad \text{..............................} (2)$$

Standard charts for grain size numbers from 1 to 8 are shown in Figures from 1 to 8

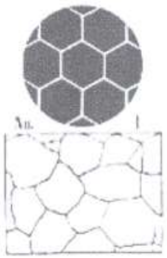


Figure 1. Upper, idealized regular shape hexagonal network for mean grain size no.1 Lower, ASTM standard grain size no.1 of irregular shape mesh Up to 1.5 gr/in² at 100x

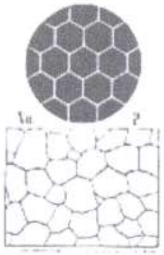


Figure 2. Upper, idealized regular shape hexagonal network for mean grain size no.2 Lower, ASTM standard grain size no.2 of irregular shape mesh. 1.5-3 gr/in² at 100x

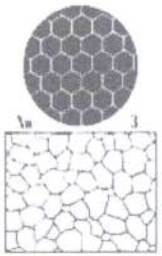


Figure 3. Upper, idealized regular shape hexagonal network for mean grain size no.3. Lower, ASTM standard grain size no.3 of irregular shape mesh. 3-6 gr/in² at 100x

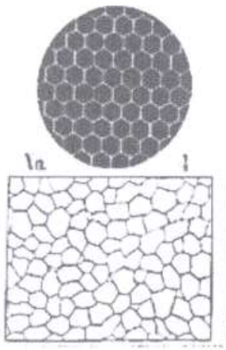


Figure 4. Upper, idealized regular shape hexagonal network for mean grain size no.4. Lower, ASTM standard grain size no.4 of irregular shape mesh. 6-12 gr/in2 at 100x.

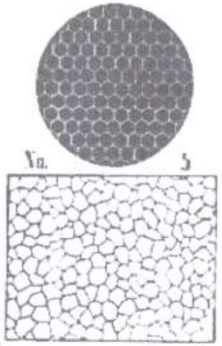


Figure 5. Upper, idealized regular shape hexagonal network for mean grain size no.5. Lower, ASTM standard grain size no.5 of irregular shape mesh. 12-24 gr/in2 at 100x.

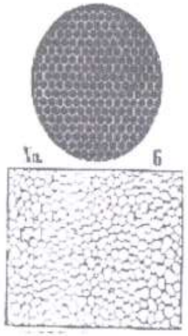


Figure 6. Upper, idealized regular shape hexagonal network for mean grain size no.6. Lower, ASTM standard grain size no.6 of irregular shape mesh. 24-48 gr/in2 at 100x.

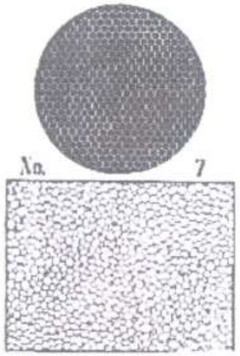


Figure 7. Upper, idealized regular shape hexagonal network for mean grain size no.7. Lower, ASTM standard grain size no.7 of irregular shape mesh. 48-96 gr/in2 at 100x.

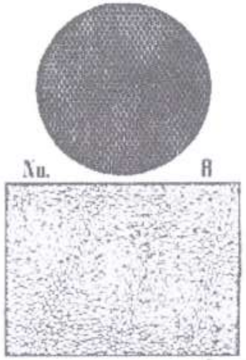


Figure 8. Upper, idealized regular shape hexagonal network for mean grain size no.8. Lower, ASTM standard grain size no.8 of irregular shape mesh. 96-192 gr/in2 at 100x

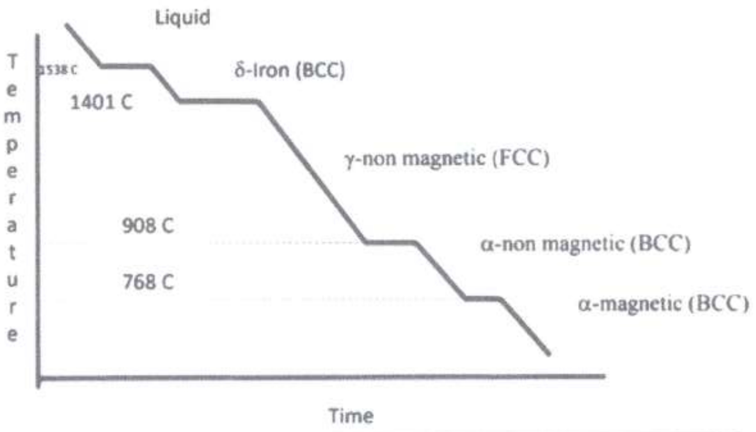
- To obtain the ASTM grain size number, one must count a minimum of at least 50 grains in each of three areas, determine the number per square inch, and convert this value to the equivalent one at 100x. Then substitution in equation 1 gives *N*.
- For grain sizes finer or coarser than the standard range of ASTM grain sizes, the magnification may be increased or decreased, still maintaining a comparison against the standard grain sizes on the chart. This enables grain sizes coarser than 1 and finer than 8 to be assessed, using the relationship:

$$N = N' + 2\,(\log(m/100))/(\log 2) \ldots\ldots\ldots\ldots (3)$$

- Where, *N'* is the apparent ASTM grain size at a magnification *m*.
- For non uniform and non equiaxed grain sizes, the ASTM method is not suitable, but it is a rapid method. Being subjective, and based upon doubtful assumptions concerning grain shape and uniformity, it is at best only a semi-quantitative method

Crystalline changes during heating

- *Allotropy (Iron)*



Steel = Iron + Carbon

Standards and Specifications of metals and alloys

Classification of materials and alloys is very important as it is:

1. Necessary not to repeat the conduction of experiments every time to explore the properties of the same alloy
2. Necessary for material selection for a certain applications.
3. Necessary to ease the communication among scientists and researchers
4. Necessary to ease the communications between companies and dealers.
5. Necessary to group materials and alloys that have the same behavior.

Methods of steel classification

The main methods of steel classification are:

1. By analysis
2. By mechanical properties
3. By use.

The widely used method of classification is by analysis.

Commonly used standard

Commonly used standards are:

1. British standard (BS)
2. American society for testing and materials (ASTM)
3. American iron and steel institute (AISI)
4. Society of automotive engineers (SAE)
5. German standard (DIN)
6. Former soviet union (commicon) standard (GOST)
7. Unified numbering system (UNS)

BS as an example

@ Each "En" designation detailed analysis range, mechanical range, conditions, and other necessary information

Example: **BS970:060A52**

060- percent of manganese

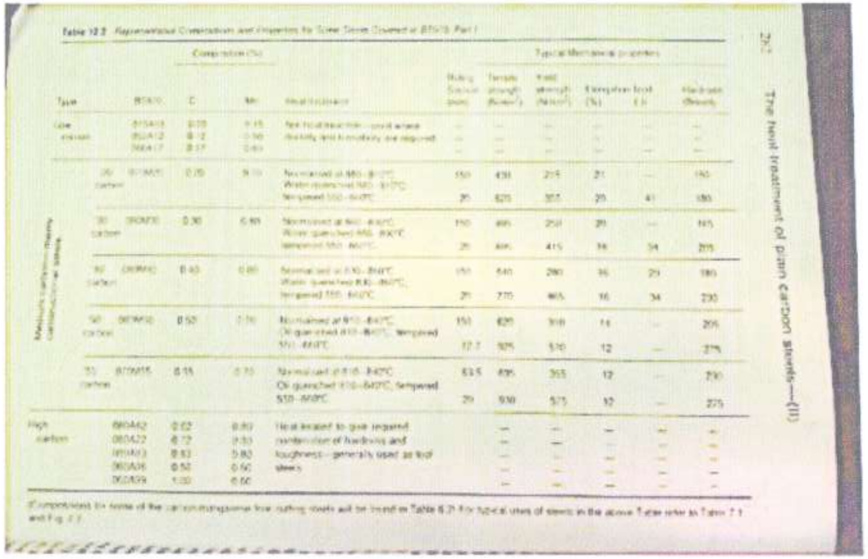
A – the requirements that the steel supplied to

(A- analysis, M-mechanical properties, H-hardenability)

52- percent of carbon

If the first three digits are 200-240 it is free cutting manganese steel. Sulphur content

Examples: Table 12.2 Higgins book



AISI and SAE

There is a minor variation between AISI and SAE standards.

AISI is a four digit system for plain carbon steel (Example: - - - -). First two digits describe the steel and the remained is the percent of carbon. Examples:

10xx – plain carbon steel

1050 - plain carbon steel with .0.5% carbon

11xx – free machining plain carbon steel with sulphure addition

Cont.

SAE three digits:

Example:

Stainless steel

2xx is achromium-nickel manganese steel non hardenable, austenitic

3xx.....

4xx......

Sometimes letter and two digits (Mxx)

M-molebdinum steel

T- tungesten steel

H- hot worked steel

O- oil hardened steel

Unified numbering system (UNS)

@ UNS provides a designation system for all present and future metals and alloys. The system was published by the SAE in 1975. SAE and ASTM are now using this system and it is proposed to the ISO.

@ UNS establishes 15 series of numbers for metals and alloys. Each UNS number consists of a single letter prefix followed by five digits. The letter is suggestive of the family of metals identified. Example: A- for aluminum, P- for precious materials

And whenever feasible, identification numbers are from existing systems. Example:

Plain carbon steel AISI1020 $\xrightarrow{\text{(becomes)}}$ G1 1020

Cont

D00001 — D99999	Specified mechanical properties
F00001 — F99999	Cast irons, Gray, malleable, pearl. ductile (nodular), carbon & low alloy steel casting
G00001 - G99999	AISI-SAE - Carbon & alloy st[illegible]
H00001 - H99999	AISI "H" steels
K00001 - K99999	Miscellaneous steels & ferrous
S00001 - S99999	Stainless steels
T00001 - T99999	Tool steels

non-ferrous metals

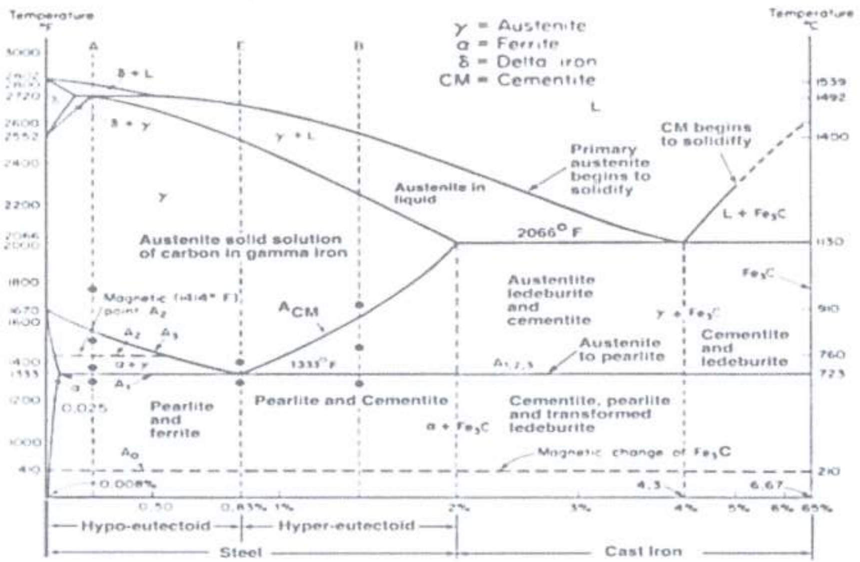
A00001 - A99999	aluminum & aluminum
C00001 - C99999	Copper & Copper alloys
E - E 99999	Rare earth and [illegible]
L - L 99999	Low melting metals
M - M 99999	Miscellaneous nonferrous metals
N - N	Nickel & its alloys
P - P	Precious alloys
R - R99999	refractory & reactive

ASTM, DIN, GOST

Individual work

Iron-Carbon Phase Diagram

Iron – Carbon/Cementite Phase Diagram



Solid phases in iron carbon diagram

1. ***Alpha Ferrite*** : This phase is an interstitial solid solution of carbon in the BCC iron crystal lattice, reaching a maximum solid solubility of 0.02% at 723 °C. The solubility of carbon in alpha ferrite decreases to 0.005% at 0 °C.
2. ***Gamma Austenite***: This phase is an interstitial solid solution of carbon in the FCC iron crystal lattice, reaching a maximum solid solubility of 2.0 % at 1128 °C. The solubility of carbon in austenite decreases to 0.8% at 723 °C.

3. ***Cementite (Fe3C):*** It is an intermetalic compound which has negligible solubility limit and a composition of 6.67% C & 93.7% Fe. It is also hard and brittle.

4. ***Delta Ferrite***: It is an interstitial solid solution of carbon in the BCC delta iron crystal lattice, reaching a maximum solid solubility of 0.09 % at 1465 °C.

Reactions in iron carbon diagram

1. ***Eutectic***

$$L\ (4.3\%\ C) \underset{\text{heating}}{\overset{\text{Cooling}}{\rightleftarrows}} \gamma\ (2.0\%\ C) + Fe3C\ (6.7\%\ C) \quad 1148\ °C$$

2. ***Eutectoid***

$$\gamma\ (0.8\%\ C) \rightleftarrows \alpha\ (0.02\%C) + Fe3C\ (6.7\%\ C) \quad 723\ °C$$

3. ***Peritectic***

$$\delta\ (0.09\%\ C) + L\ (0.53\%\ C) \rightleftarrows \gamma \quad 1459\ °C$$

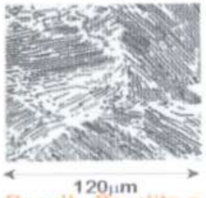
Development of Microstructure

- *Eutectoid alloy*
- *Hypo-eutectoid*
- *Hyper eutectoid*

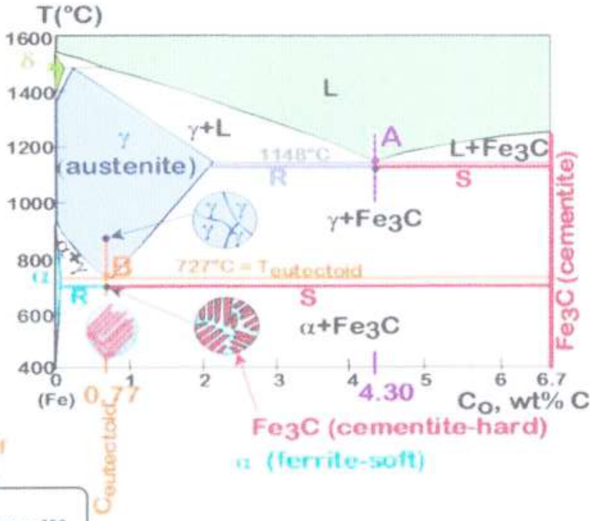
IRON-CARBON (Fe-C) PHASE DIAGRAM

(eutectoid alloy structure)

- **2 important points**
  - **-Eutectic (A):** $L \Rightarrow \gamma + Fe_3C$
  - **-Eutectoid (B):** $\gamma \Rightarrow \alpha + Fe_3C$



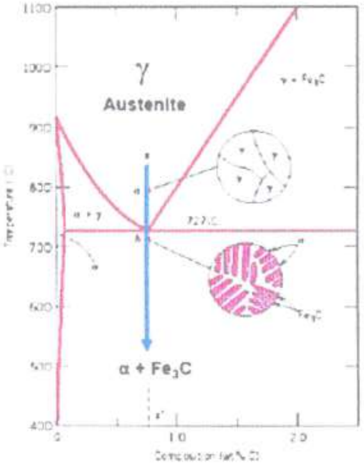
Result: Pearlite = alternating layers of α and Fe_3C phases.



Till 0.77 Carbon

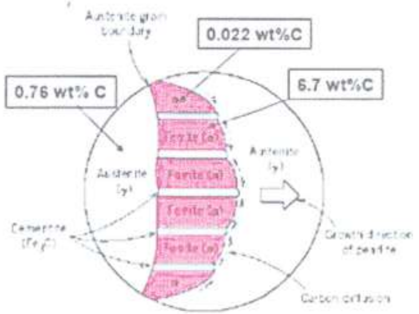
Tensile strength (MPa) = 700x%Carbon + 350

Pearlite Formation

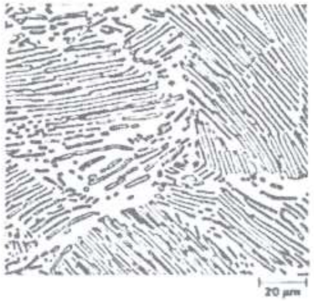


- Austenite precipitates Fe3C at Eutectoid Transformation Temperature (727°C).
- When slow cooled, this is Pearlite (looks like Mother of Pearl)

Diffusion of Carbon in Pearlite

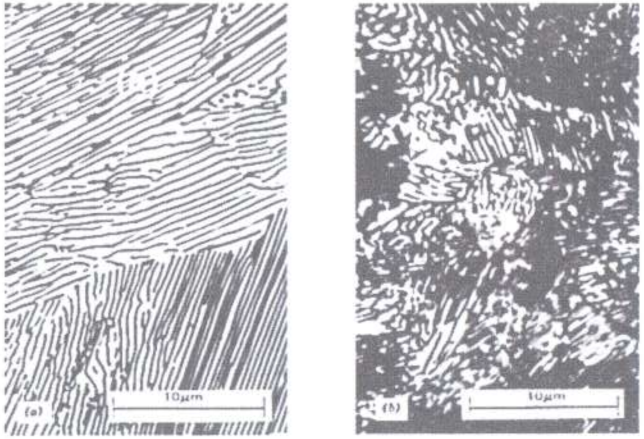


- Schematic representation of the formation of pearlite from austenite
  - direction of arrows indicates carbon diffusion



- Micrograph of eutectoid steel, showing pearlite microstructure.
  - α ferrite (light)
  - Fe_3C (dark)

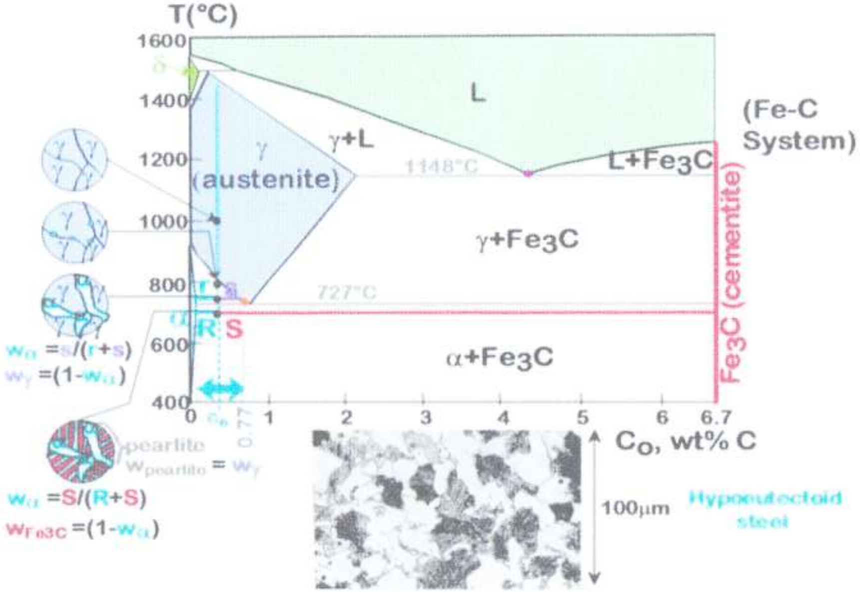
Morphology of Pearlite



(a) coarse pearlite

(b) fine pearlite 3000X

HYPO EUTECTOID STEEL



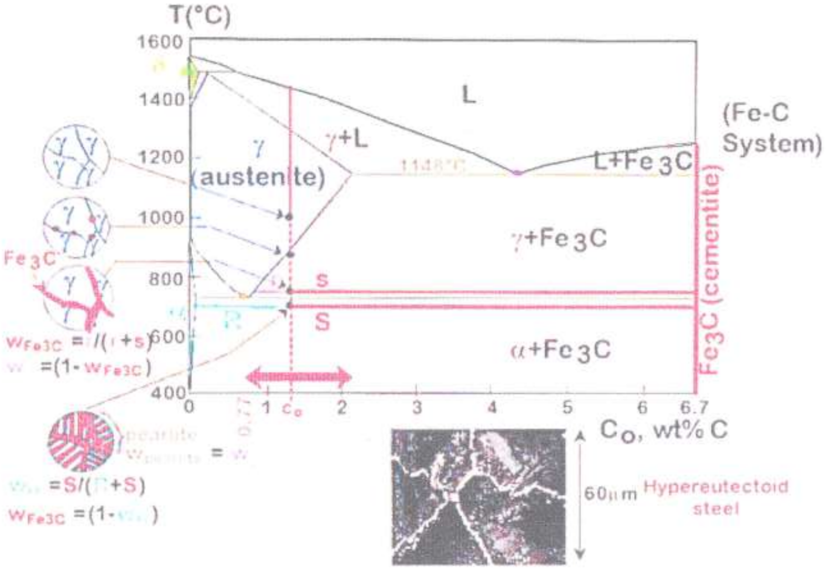
$w_\alpha = s/(r+s)$

$w_\gamma = (1-w_\alpha)$

$w_\alpha = S/(R+S)$

$w_{Fe3C} = (1-w_\alpha)$

HYPER UTECTOID STEEL

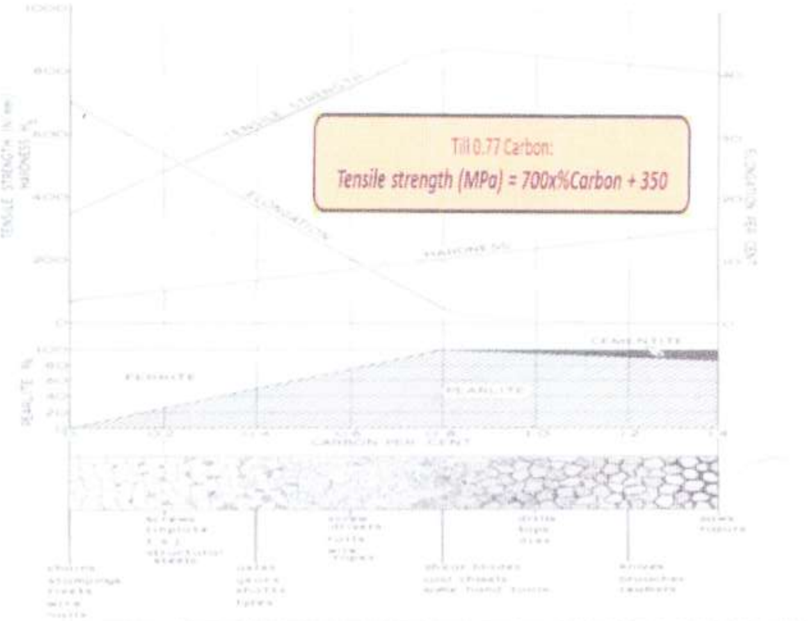


$w_{Fe3C} = r/(r+s)$

$w = (1-w_{Fe3C})$

$w = S/(R+S)$

$w_{Fe3C} = (1-w)$



Till 0.77 Carbon:

Tensile strength (MPa) = 700x%Carbon + 350

A diagram showing the relationship between carbon content, microstructure and mechanical properties of plain carbon steels in the normalised condition. Typical uses of these steels are also indicated.

The influence of alloying element

- ***On phase diagram***:

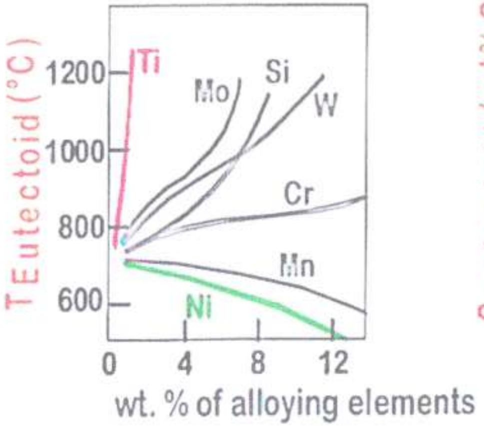
1. Altering the position of the boundaries
2. Altering the shape of the phase field.

- ***The extent of influence depends on***:

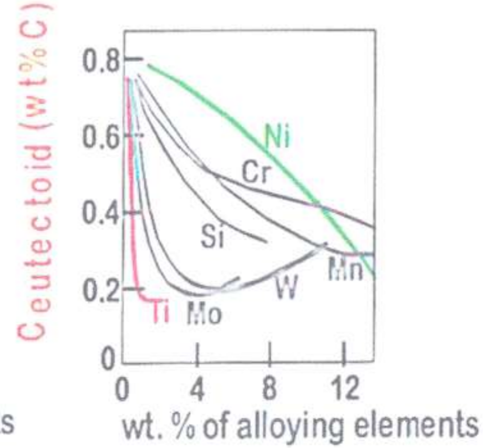
1. The type of alloying element
2. The concentration of alloying element

ALLOYING STEEL WITH MORE ELEMENTS

- Teutectoid changes:

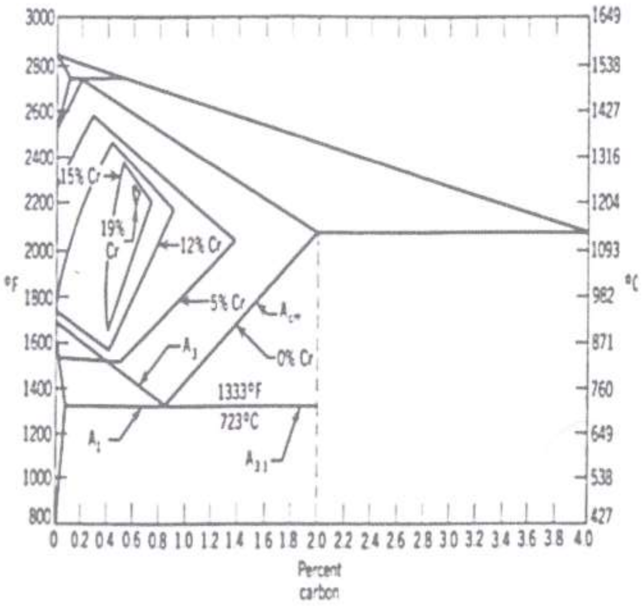


- Ceutectoid changes:

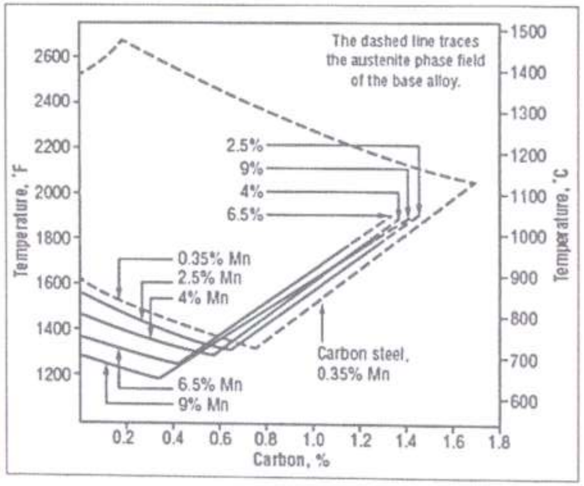


ALLOYING ELEMENTS AND THE IRON-CARBON DIAGRAM

Alloying elements move the transformation lines of the iron-carbon diagram. A common alloying element is chromium. Considering the austenite area of the iron-carbon diagram, it can be seen that the effect of increasing chromium is to decrease the austenite range (Figure below). This will increase the ferrite range. Many other alloying elements are ferrite promoters also, such as molybdenum, silicon, and titanium. Nickel and manganese tend to enlarge the austenite range and lower the transformation temperature (austenite to ferrite). A large percentage of these metals will cause steels to remain austenitic at room temperature. Examples are 18-8 stainless steel and 14 percent manganese steel. The A^-Ay ^ line is also lowered by rapid cooling. Any alloy addition will move the eutectoid point to the left (with a few exceptions such as copper) or, in other words, lower the carbon content of the eutectoid composition.



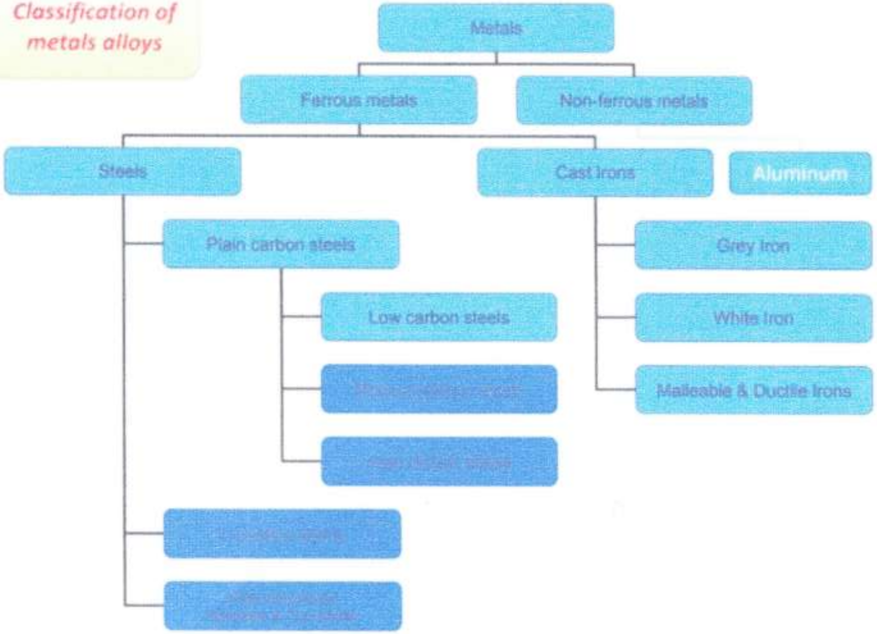
The effect of chromium on the austenite range of steel. *(Machine Tools and Machining Practices)*



The influence of adding Mn

Heat treatment Processes

Classification of metals alloys



- Metals
  - Ferrous metals
    - Steels
      - Plain carbon steels
        - Low carbon steels
    - Cast Irons
      - Grey Iron
      - White Iron
      - Malleable & Ductile Irons
  - Non-ferrous metals
    - Aluminum

Main Subjects of Heat treatment to be discussed in this Course:

1. *Heat treatment of ferrous alloys*
2. *Heat treatment of non ferrous alloys*
3. *Heat treatment of cast iron*
4. *Heat treatment of welding*

Heat treatment of ferrous alloys

It is the procedure for producing metals or alloys with different or demanded properties by heating them to a predetermined temperature, then cooling them using different media (different cooling rates) which leads to different microstructure and different properties of the alloys without changing the product shape.

Heat Treatment *is often associated with:*

1. *increasing the strength of material*
2. *altering certain manufacturability objectives such as improving machining,*
3. *Improving formability*
4. *Restoring ductility after a cold working operation*
5. *It is a very enabling manufacturing process that can not only help other manufacturing process, but can also improve product performance by increasing strength or other desirable characteristics.*

Steels *are particularly suitable for heat treatment, since they respond well to heat treatment and the commercial use of steels exceeds that of any other material. Steels are heat treated for one of the following reasons:*

1. ***Softening***
2. ***Hardening***
3. ***Material Modification***

Softening: *Softening is done to reduce strength or hardness, remove residual stresses, improve toughnesss, restore ductility, refine grain size or change the electromagnetic properties of the steel. Restoring ductility or removing residual stresses is a necessary operation when a large amount of cold working is to be performed, such as in a cold-rolling operation or wiredrawing. Annealing — full Process, spheroidizing, normalizing and tempering — austempering, martempering are the principal ways by which steel is softened.*

Hardening: *Hardening of steels is done to increase the strength and wear properties. One of the pre-requisites for hardening is sufficient carbon and alloy content. If there is sufficient Carbon content then the steel can be directly hardened. Otherwise the surface of the part has to be Carbon enriched using some diffusion treatment hardening techniques.*

Material Modification:

Heat treatment is used to modify properties of materials in addition to hardening and softening.

These processes modify the behavior of the steels in a beneficial manner to maximize service life, e.g., stress relieving, or strength properties, e.g., cryogenic treatment, or some other desirable properties, e.g., spring aging.

Heat treatment methods –CASE STUDY: Plain Carbon Steel:

Heat treatment methods –CASE STUDY: Plain Carbon Steel:

The main methods of heat treatment that will be discussed here are:

1. Annealing

- **Full annealing**
- **Spherodize annealing**
- **Stress relief annealing**
- **Process annealing**

2. Normalizing
3. Hardening
4. Tempering
5. Treatments using isothermal transformation (I-T) diagrams
6. Other Processes

Annealing:

__Full anneal__ It is heating the part in the furnace to about 28 °C above A3 before 0.8% C and to about 28 °C above A1 after 0.8% C, then cooling very slowly in the furnace or in an insulating material. The microstructure becomes coarse pearlite and ferrite.

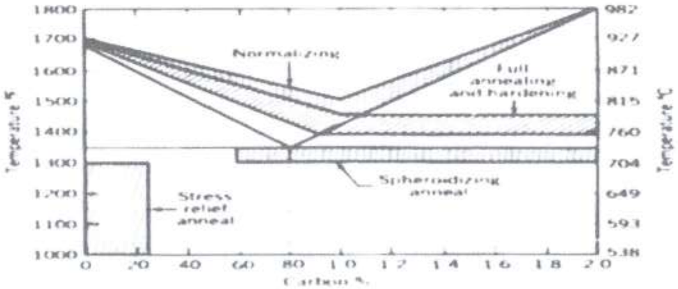


FIGURE 1. **Temperature ranges used for heat-treating carbon steel.** ***(Machine Tools and Machining Practices)***

__Purpose__: To increase ductility

Examples:

1. *For easier machining of tool steels that have more than 0.8%C*
2. *For welding when iron contains less than 0.8%C*

** Tensile strength of Hypoeutectoid alloy =*

(40 000 x % of ferrite + 120 000 x % of pearlite)

In the microstructure

Microstructure after Full annealing:

Spherodize anneal: *It is heating the material to a temperature close to 704 °C (lower than A1), holding it for four hours then cooling it in the furnace. The microstructure is spherical or globular carbide grains in the steel rather than lamellar structure.*

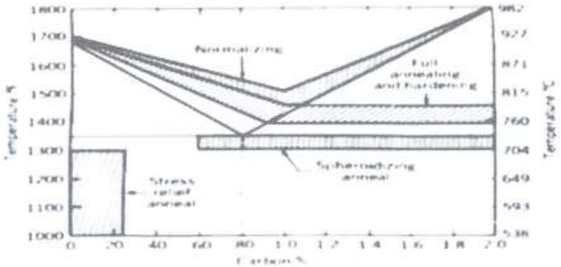


FIGURE 1. Temperature ranges used for heat-treating carbon steel. *(Machine Tools and Machining Practices)*

Example:

To improve the machinability of high carbon steels (0.8 – 1.7 % C).

- * *When spherodize low carbon steels(), their machinability gets poorer, since they become gummy and soft causing edge build up*

Microstructure after spherodize annealing:

Stress relief anneal: *It is heating of low carbon steel to 510 °C after getting stressed by cold working such as rolling, pressing, welding...etc.*

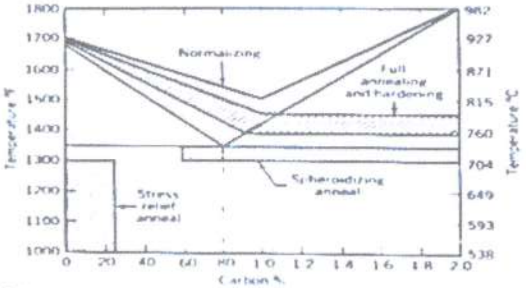


FIGURE 1. Temperature ranges used for heat-treating carbon steel. *(Machine Tools and Machining Practices)*

Stress relief

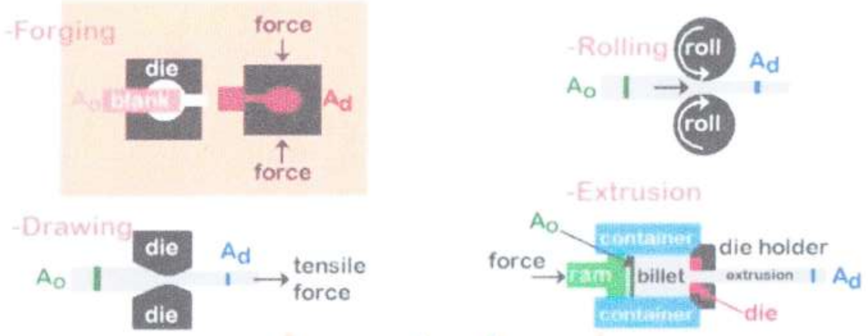
Purpose: *elimination of the cold working effect.*

The microstructure: *the distorted grains reform or recrystallize into new softer ones after the annihilation of dislocations.*

The pearlite and some other forms of iron carbide remain unaffected by this hea treatment.

COLD WORK (%CW)

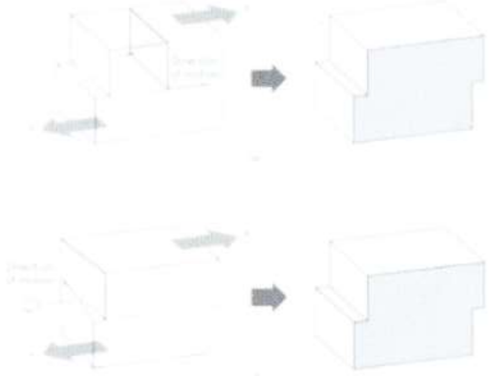
- Common forming operations change the cross sectional area:



$$\%CW = \frac{A_o - A_d}{A_o} \times 100$$

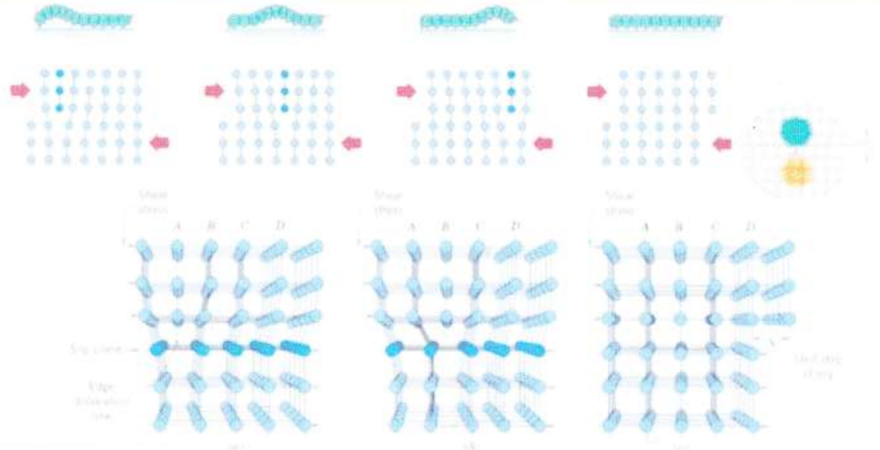
Dislocations & Plastic Deformation (PD)
Basic Concepts

- ***Slip***: the process by which plastic deformation is produced by dislocation motion.
    - ***Slip Plane***: the crystallographic plane along which the dislocation line traverses (Figure 7.1).
- Macroscopic plastic deformation simply corresponds to permanent deformation that results from the movement of dislocations, or slip, in response to an applied shear stress.



The formation of a step on the surface of a crystal by the motion of (*a*) an edge dislocation and (*b*) a screw dislocation. Note that for an edge, the dislocation line moves in the direction of the applied shear stress ; for a screw, the dislocation line motion is perpendicular to the stress direction.

Dislocations & Plastic Deformation (PD)
Creation of Dislocations



Atomic rearrangements that accompany the motion of an edge dislocation as it moves in response to an applied shear stress. (*a*) The extra half- lane of atoms is labeled *A*. (*b*) The dislocation moves one atomic distance to the right as *A* links up to the lower portion of plane *B*; in the process, the upper portion of *B* becomes the extra half-plane. (*c*) A step forms on the surface of the crystal as the extra half-plane exits.

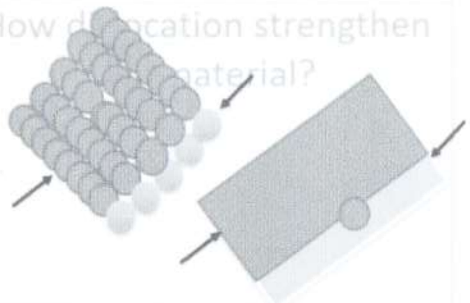
DISLOCATIONS DURING COLD WORK

- Ti alloy after cold working:

- Dislocations entangle with one another during cold work.
- Dislocation motion becomes more difficult.

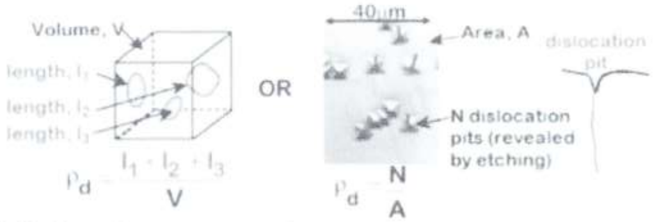
Dislocation motion video
https://www.youtube.com/watch?v=EXbiEopDJ_g

How dislocation strengthen material?



RESULT OF COLD WORK

- Dislocation density (ρ_d) goes up:
  Carefully prepared sample: $\rho_d \sim 10^3$ mm/mm^3
  Heavily deformed sample: $\rho_d \sim 10^{10}$ mm/mm^3
- Ways of measuring dislocation density:



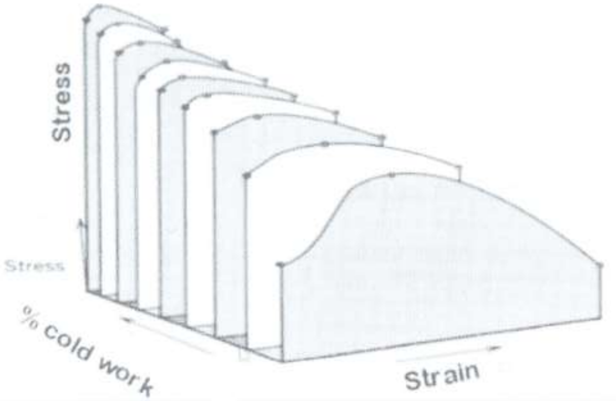
$$\rho_d = \frac{l_1 + l_2 + l_3}{V}$$

$$\rho_d = \frac{N}{A}$$

- Yield stress increases as ρ_d increases:

IMPACT OF COLD WORK

- Yield strength (σ_y) increases.
- Tensile strength (TS) increases.
- Ductility (%EL or %AR) decreases.



EFFECT OF HEATING AFTER %CW

3 Annealing stages

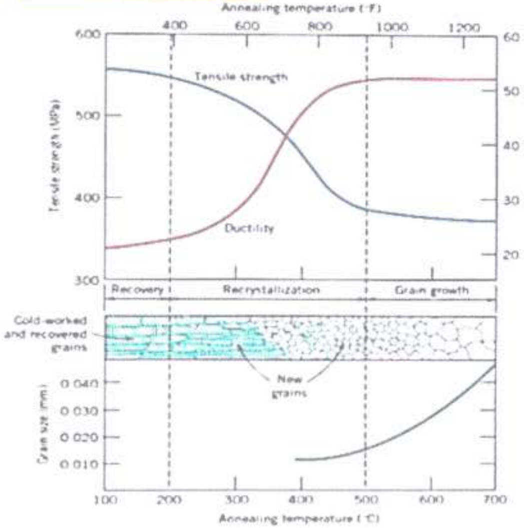


Figure The influence of annealing temperature (for an annealing time of 1 h) on the tensile strength and ductility of a brass alloy. Grain size as a function of annealing temperature is indicated. Grain structures during recovery, recrystallization, and grain growth stages are shown schematically.

The recrystallization temperature for the brass alloy is about 450° C

Hints

- **Dislocations are observed primarily in metals and alloys.**
- Here, strength is increased by making dislocation motion difficult.
- Particular ways to increase strength are to:
  --decrease grain size
  --solid solution strengthening
  --precipitate strengthening
  --cold work
- Heating (annealing) can reduce dislocation density and increase grain size.

Stress relief Mechaniams (Recovery and Recrystallization) and Grain Growth

Recovery is a low-temperature effect in which there is little or no visible change in the microstructure. Electrical conductivity is increased, and often a decrease in hardness is noted.

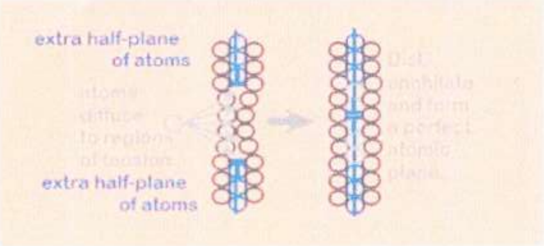
During *recovery*, some of the stored internal strain energy is relieved by virtue of dislocation motion (in the absence of an externally applied stress), As a result of enhanced atomic diffusion at the elevated temperature.

There is some reduction in the number of dislocations, and dislocation configurations are produced having low strain energies. In addition, physical properties such as electrical and thermal conductivities are recovered to their precold-worked states.

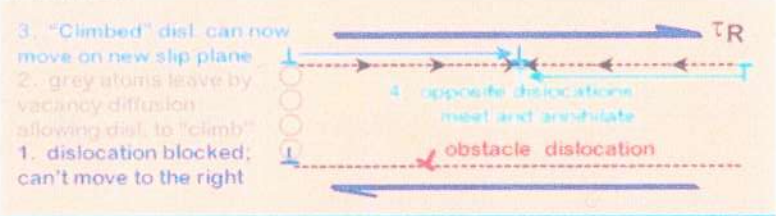
RECOVERY

Annihilation reduces dislocation density.

- Scenario 1



- Scenario 2

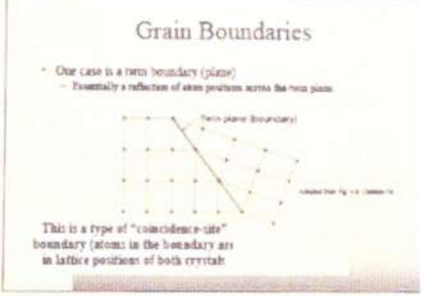


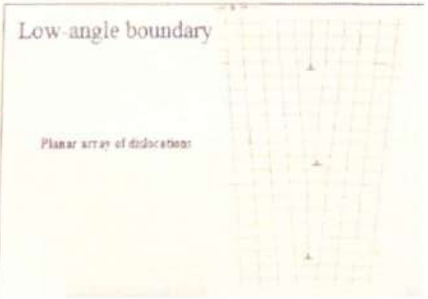
Dislocation climb and glide video
https://www.youtube.com/watch?v=[illegible]

Recrystallization releases much larger amounts of energy than does recovery. The flattened, distorted grains are sometimes reformed to some extent during recovery into polygonal grains while some rearrangement of defects such as dislocations takes place. Recrystallization not only releases much larger amounts of stored energy but new grains are formed by the nucleation of stressed grains and the joining of several grains to form larger ones

Recrystallization: formation of a new set of strain-free and equiaxed grains that have low dislocation densities and are characteristic of the precold-worked condition.

- *The driving force to produce this new grain structure is the difference in internal energy between the strained and unstrained material.*
- *Recrystallization of cold-worked metals may be used to refine the grain structure.*





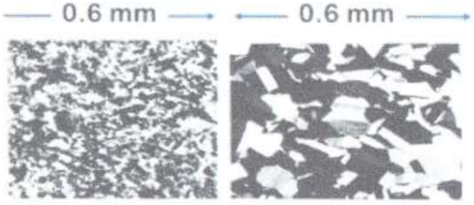
RECRYSTALLIZATION

Figure Photomicrographs showing several stages of the recrystallization and grain growth of brass. (*a*) Cold-worked (33%CW) grain structure. (*b*) Initial stage of recrystallization after heating 3 s at 580° C; the very small grains are those that have recrystallized. (*c*) Partial replacement of cold-worked grains by recrystallized ones (4 s at 580° C). (*d*) Complete recrystallization (8 s at 580° C). (*e*) Grain growth after 15 min at 580° C. (*f*) Grain growth after 10 min at 700° C.

GRAIN GROWTH

***Grain growth** is the process of joining of adjacent grains. Grain boundaries migrate to new positions, which charges the orientation of the crystal structure.*

- At longer times, larger grains consume smaller ones.
- Why? Grain boundary area (and therefore energy) is reduced.



After 8 s, 580C

After 15 min, 580C

- Empirical Relation:

exponent typ. ~ 2

grain diam. at time t.

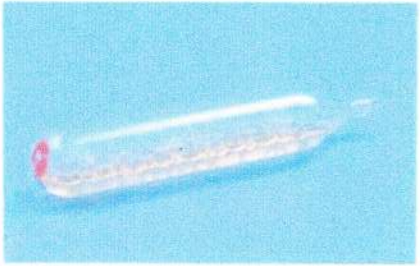
$$d^n - d_o^n = Kt$$

coefficient dependent on material and T.

elapsed time

Grain Growth Simulation

A glass vial containing a liquid that foams. Shaking results in a fine foam, which slowly coarsens with time. The coarsening process is somewhat analogous to grain growth in solids.



The same vial, after allowing some time for the foam to coarsen. The process occurs in order to reduce the surface per unit volume.

Link to grain growth simulation https://upload.wikimedia.org/wikipedia/commons/3/38/Grgr3d_small.gif

Process anneal: *It is the anneal, between a series of cold working operations, in which, the grains reform to their original soft and ductile conditions.*

It is carried out in a closed container with inert gas to prevent oxidation of the surface.

Purpose:

to be able to continue The forming process by eliminating the cold working effect.

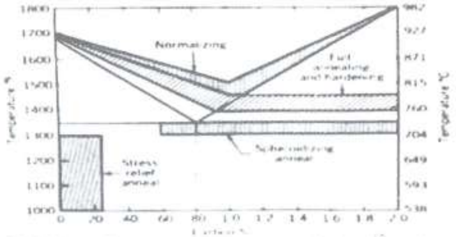
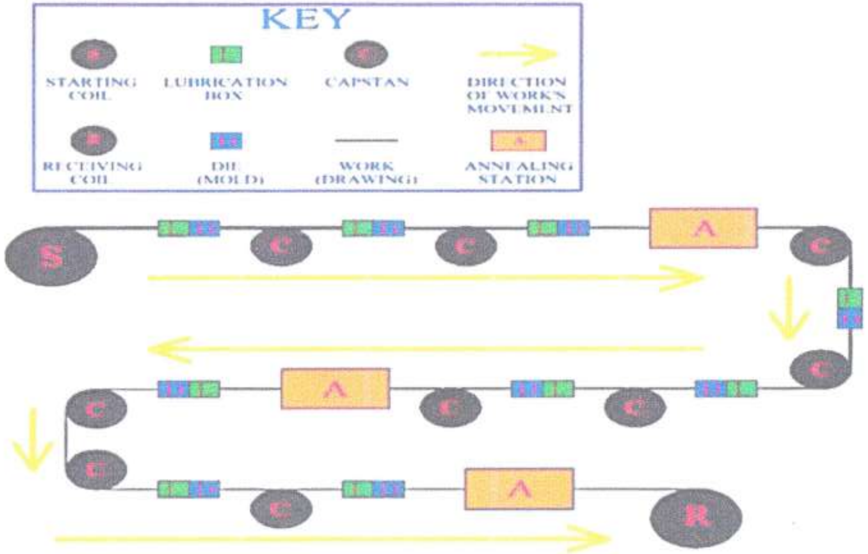


FIGURE 1. Temperature ranges used for heat-treating carbon steel. *(Machine Tools and Machining Practices)*

WIRE DRAWING



Normalizing: It is heating the piece to 56 °C above A3 then cooling it in still air. When the content of carbon is more than 0.8%, a higher temperatures are required. The resultant microstructure is fine pearlite.

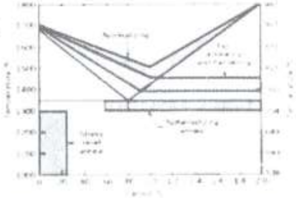


FIGURE 1. Temperature ranges used for heat-treating carbon steel (Machine Tools and Machining Practices)

Purpose:

1. To correct the irregular grain structure after casting or forging
2. To improve machinability of low carbon steel because it becomes gummy when annealed

---

Microstructure Normalizing:

Hardening: *It is heating the piece to a temperature above A3 before 0.8% C and to a temperature above A1 after 0.8 % C then suddenly cooling it with a high rate of cooling. The microstructure formed is martensite.*

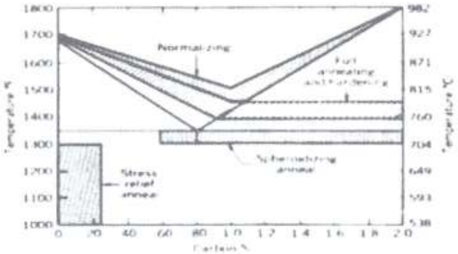


FIGURE 1. Temperature ranges used for heat-treating carbon steel (Machine Tools and Machining Practices)

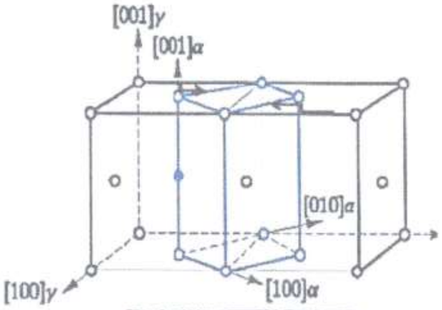
Purpose: *to increase the strength and wear properties.*

Martensite

- ✖ *Diffusionless transformation of FCC to BCT (more volume!)*
- ✖ *Needle-like structure*
- ✖ *Very hard & very brittle.*
- ✖ *Metastable*

Martensite Transformation *depends on:*

1. Hardenability of the material
2. Mass of the part
3. Severity of quenching media



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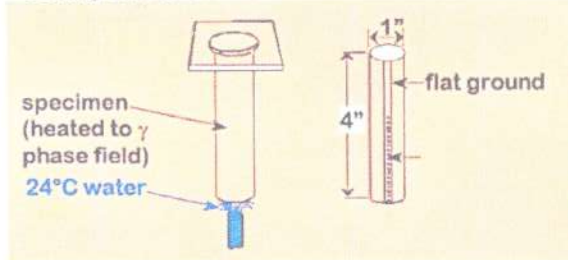
1. Hardenability: *It is the Ability of an alloy to be hardened by the formation of martensite.*

- Hardenability *is dependent upon the chemical composition of the steel alloy.*

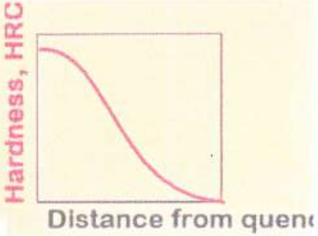
For example: the addition of Nickel, Chromium and Molybdenum will slow the transformation to other phases and allow more martensite to form.

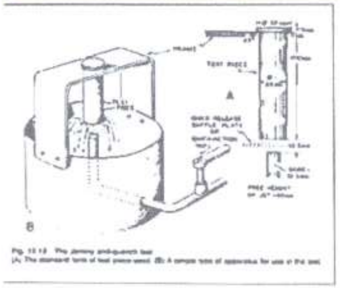
Hardenability Testing

- Jominy end quench test is used to measure hardenability.



- Hardness versus distance from the quenched end.



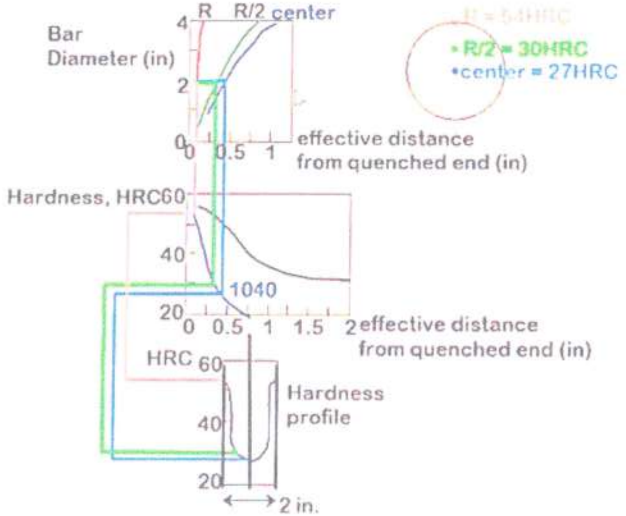


The Jominy End-Quench Test

One standard procedure that is widely utilized to determine hardenability is the **Jominy end-quench test.** With this procedure, except for alloy composition, all factors that may influence the depth to which a piece hardens (i.e., specimen size and shape, and quenching treatment) are maintained constant. A cylindrical specimen 1 in. (25 mm) in diameter and 4 in. (100 mm) long is austenitized at a prescribed temperature for a prescribed time. After removal from the furnace, it is quickly mounted in a fixture as diagrammed in Figure 11.2*a*. The lower end is quenched by a jet of water of specified flow rate and temperature. Thus, the cooling rate is a maximum at the quenched end and diminishes with position from this point along the length of the specimen. After the piece has cooled to room temperature, shallow flats 0.015 in. (0.4 mm) deep are ground along the specimen length and Rockwell hardness measurements are made for the first 2 in. (50 mm) along each flat (Figure 11.2*b*); for the first ½ in., hardness readings are taken at $\frac{1}{16}$-in. (1.6 mm) intervals, and for the remaining 1½ in., every ⅛ in. (3.2 mm). A hardenability curve is produced when hardness is plotted as a function of position from the quenched end.

PREDICTING HARDNESS PROFILES

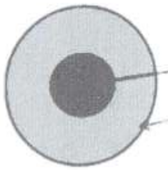
- Ex: Round bar, 1040 steel, water quenched, 2" diam.



2. Mass effect (Depth of Hardening)

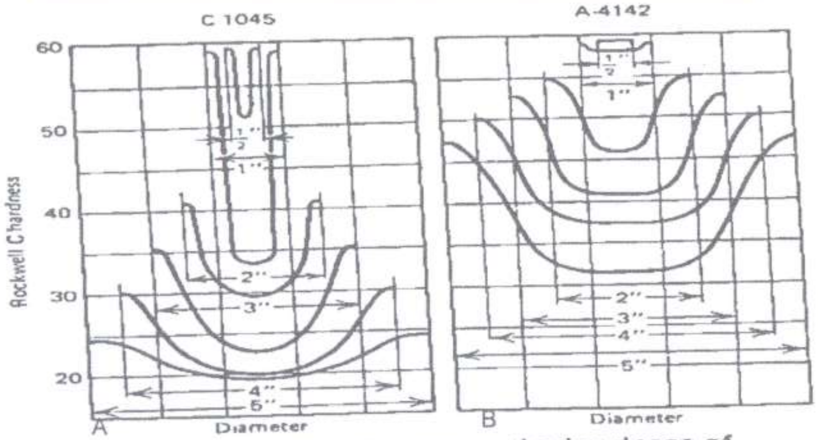
- *Due to the mass effect, not all the section of a large component may be hardened due to too slow cooling rate.*
- *This may leave a soft core, or in extreme cases prevent hardening altogether.*

- *Effect of geometry: When surface-to-volume ratio increases:*
  - *–cooling rate increases*
  - *–hardness increases*



Position	Cooling rate	Hardness
center	small	small
surface	large	large

1. A only and B only give mass and size effect
2. A compared to B gives the type of the alloy effect



The effect of mass on the hardness of several cylindrical (round) quenched specimens of different diameters. (Courtesy of Pacific Machinery & Tool Steel Company)

3. SEVERETY OF QUENCHING MEDIUM

- **Effect (Severity) of quenching medium**

Medium	Severity of Quench	Hardness
air	small	small
oil	moderate	moderate
water	large	large

Tempering: *It is heating the piece of steel that was hardened by quenching to a temperature below A1 (about 200 – 450 °C). At this temperature martensite transforms to the equilibrium structure of ferrite and cementite.*

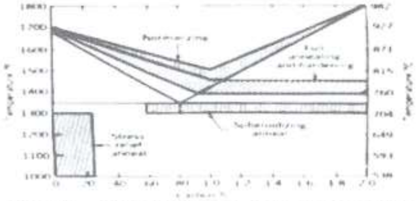


FIGURE 1. Temperature ranges used for heat-treating carbon steel *(Machine Tools and Machining Practices)*

Purpose: *It is done for the hardened structure to increase their toughness properties and their ductility and to relief the structure from the stressed state of the distored lattice.*

- **Tempering temperature**: *The higher the tempering temperature, the more martensite transforms and the softer and tougher the piece.*
- *Tempering color chart:*

Temper Color Chart

Degrees		Oxide Color	Suggested Uses for Carbon Tool Steels
C°	F°		
220	425	Light straw	Steel-cutting tools, files, and paper cutters
240	462	Dark straw	Punches, dies
258	490	Gold	Shear blades, hammer faces, center punches, and cold chisels
260	500	Purple	Axes, wood-cutting tools, and striking faces of tools
282	540	Violet	Springs, screwdrivers
304	580	Pale blue	Springs
327	620	Steel gray	Cannot be used for cutting tools

HARDER — SOFTER

Recovery, Recrystallization and Grain Growth

Recovery *is a low-temperature effect in which there is little or no visible change in the microstructure. Electrical conductivity is increased, and often a decrease in hardness is noted.*

Recrystallization *releases much larger amounts of energy than does recovery. The flattened, distorted grains are sometimes reformed to some extent during recovery into polygonal grains, while some rearrangement of defects such as dislocations takes place. Recrystallization not only releases much larger amounts of stored energy but new grains are formed by the nucleation of stressed grains and the joining of several grains to form larger ones.*

Grain growth *is the process of joining of adjacent grains. Grain boundaries migrate to new positions, which changes the orientation of the crystal structure.*

Heat Treatments abbreviations

- *A – Furnace Annealed – Slow cooled*
- *N - Normalized - Air cooled.*
- *O - Oil Quenched*
- *WQ – Water quenched.*
- *WT(370)– Water quenched, tempered at 370°C for 1 hour.*
- *WT(705)– Water quenched, tempered at 705°C for 1 hour.*

Isothermal Transformation (I-T) Diagrams:

Isothermal Transformation (I-T) Diagrams:

Once it was discovered that **the time and temperature of austenite transformation had a profound influence on the transformation products, a new kind of graph or diagram was needed.** The iron-carbon diagram would not do, because it represents equilibrium or slow cooling and austenite transformation takes place under non-equilibrium conditions with various cooling rates. Austenite is unstable below the A1 line on the iron-carbon diagram and almost immediately begins to transform to some product such as pearlite or bainite. **An I-T diagram** shows this process very well.

---

sothermal Transformation (I-T) Diagrams:

t is the heat treatment process that uses the Temperature – Time - Transformation (TTT) curves. (*I-T diagrams are also called the Bain S-Curve or T-T-T (time-temperature-transformation) diagrams*)

TTT Curve: *It is a graphical representation of the cooling of the specimen that relates the microstructure to temperature and time.*

Purpose: *this process assumes that the temperature of the piece is held constant for a period of time before cooling.*

Construction of the TTT Diagram

When plotting an I-T diagram, three facts should be kept in mind:

1. When austenite is cooled below the A1 line to a particular temperature and held at that temperature, it will begin to transform in a given time and will complete the transformation after a given time peculiar to that steel.

2. Martensite is formed only at relatively low temperatures and almost instantaneously.

3. If austenite transforms at any point in the transformation to a structure that is stable at room temperature, rapid cooling will not change the product already transformed, but the remaining untransformed austenite will form martensite.

Construction of the TTT Diagram

4. Data for isothermal transformation diagrams are obtained by heating large numbers of small steel specimens of a specific kind of steel to the austenitization temperature (Figure below). They are then abruptly transferred to furnaces or molten salt baths that have been heated to predetermined temperatures below the critical line A1.

5. To study the transformation at 1200°F (649°C), a set of specimens is held at 1200°F (649°C) constant temperature (isothermal). At regular time intervals a specimen is removed and rapidly quenched in iced brine. Microscopic examination will then show martensite if transformation has not yet started, but will show martensite and pearlite (in this case) if transformation has started, and only pearlite if transformation is complete. A mark is placed on the graph, indicating the time and temperature.

Construction of the TTT Diagram

This procedure is repeated at other temperatures until the entire graph is plotted for that particular steel (Figure 3). The vertical scale on the left represents temperature and the horizontal scale on the bottom represents time. It is plotted on a log scale that corresponds to 1 minute, 1 hour, 1 day, and 1 week. The letters Ms can be found at a specific temperature for each kind of steel. Ms represents the temperature at which austenite begins to transform to martensite during cooling. The Mf temperature is the point at which the transformation of austenite to martensite is completed or near 100 percent during cooling. This is sometimes replaced by a percentage of transformation.

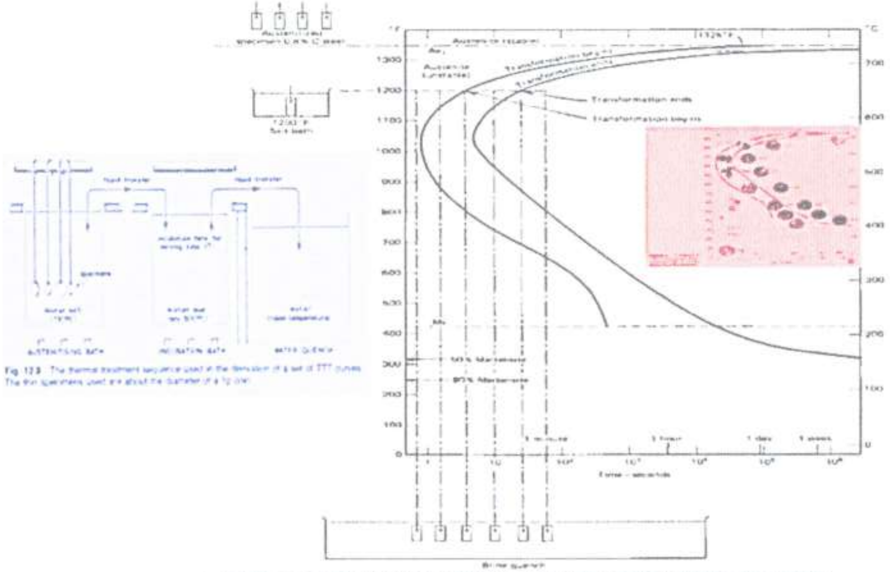
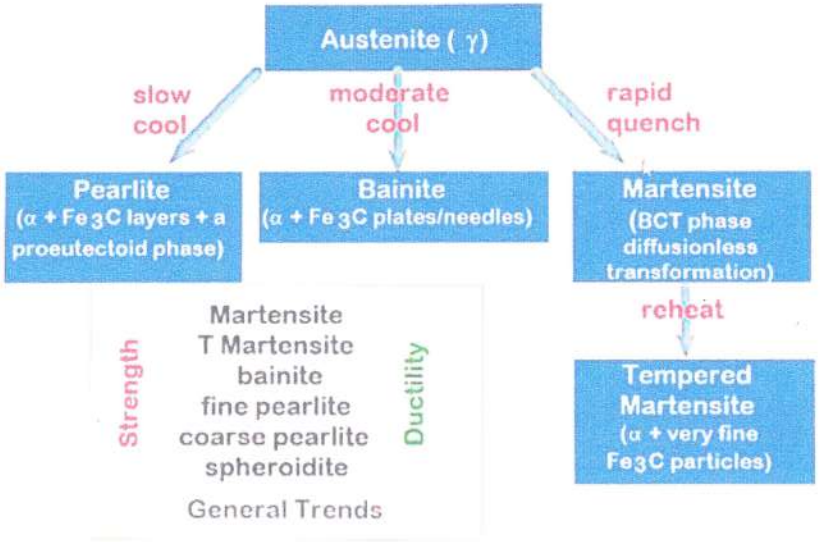


FIGURE 3. Method of plotting I-T diagram. Austenitized specimens are placed in a furnace or salt bath and held at a specific temperature. They are removed at specific time intervals and quenched in brine. Each specimen, having been marked for its time period, is then prepared and checked with a microscope for its lack of transformation products (it would be fully martensite in that case) or its percentage of transformation and at what time interval transformation began and ended. Probably many more specimens would be used for a single temperature plot than this diagram shows.

PROCESSING OPTIONS



Austenite (γ)

slow cool → **Pearlite** (α + Fe_3C layers + a proeutectoid phase)

moderate cool → **Bainite** (α + Fe_3C plates/needles)

rapid quench → **Martensite** (BCT phase diffusionless transformation)

reheat → **Tempered Martensite** (α + very fine Fe_3C particles)

Strength

Martensite
T Martensite
bainite
fine pearlite
coarse pearlite
spheroidite

Ductility

General Trends

What About Cooling Rates?

- Faster cooling gives "non-equilibrium microconstituents"…
  - –Bainite
  - –Martensite
  - –And more!
- To know what microconstituents are present, you must look at cooling curve diagrams

Microconstituents vs. Cooling Rate

In creasing Cooling Rate

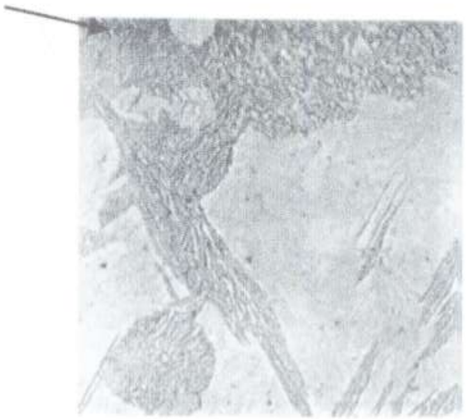
- **Spheroidite:** Spherical “globs” of Fe3C in Ferrite
- **Pearlite:** Layers of α ferrite and Fe3C
  - Course Pearlite
  - Fine Pearlite
- **Bainite:** 200 – 500 °C Transformation
- **Martensite:** Rapid Cooling

Spheroidite

- If tempered for a long time, Fe3C forms “spheres” and grows inside Ferrite.
- Very soft, easy to machine

Bainite

- Upper (550-350°C)
  - Rods of Fe3C
- Lower (350-250°C)
  - Fe3C Precipitates in Plates of Ferrite
- It is still Ferrite and Cementite! It’s just acicular.



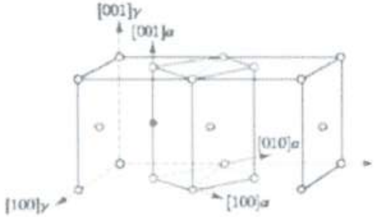
Martensite

Reminder:

-Diffusionless transformation of FCC to BCT (more volume!)

-Lenticular structure

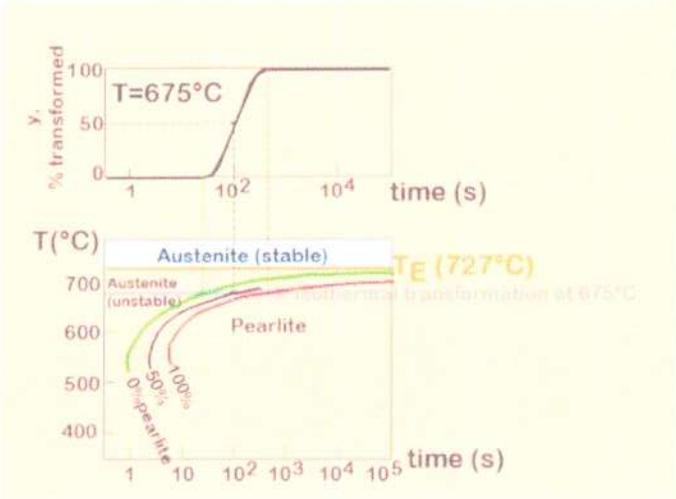
-Very hard & very brittle.



General Demonstration:
Isothermal Diagrams

ISOTHERMAL TRANSFORMATION DIAGRAMS

- Fe-C system, $C_o = 0.77wt\%C$
- Transformation at T = 675C.

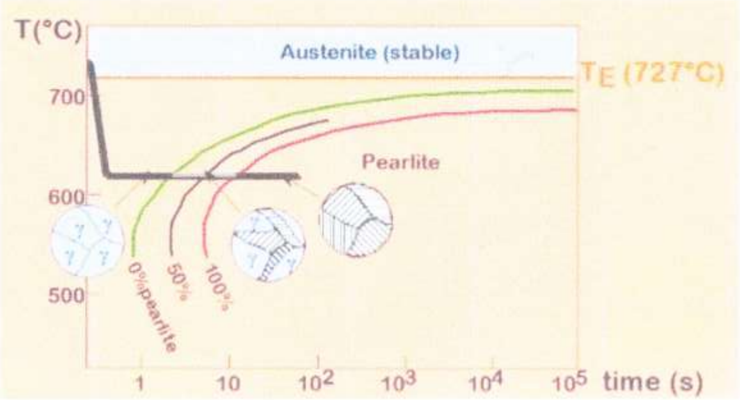


Development of the Microstructure

- *COOLING HISTORY Fe-C SYSTEM*

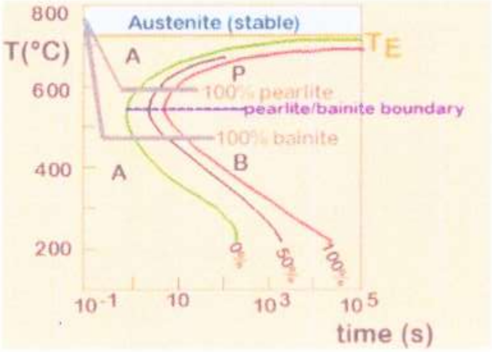
Eutectoid composition, $C_o = 0.77wt\%C$

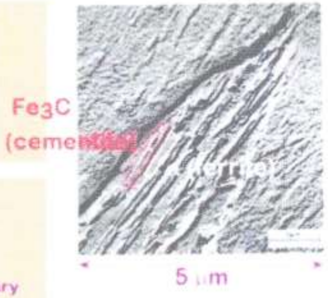
- Begin at T > 727C
- Rapidly cool to 625C and hold isothermally.



NON-EQUIL TRANSFORMATION PRODUCTS: Fe-C

- Bainite:
  - --α lathes (strips) with long rods of Fe_3C
  - --diffusion controlled.
- Isothermal Transf. Diagram



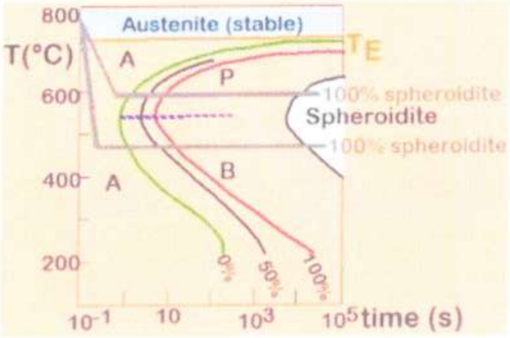


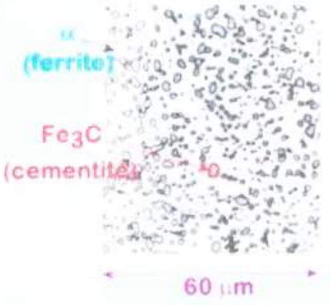
Bainite reaction rate:

$$r_{bainite} = e^{-Q/RT}$$

OTHER PRODUCTS: Fe-C SYSTEM (1)

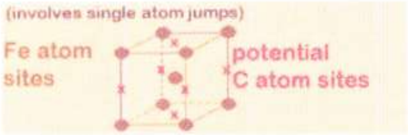
- Spheroidite:
  - --α crystals with spherical Fe_3C
  - --diffusion dependent.
  - --heat bainite or pearlite for long times
  - --reduces interfacial area (driving force)
- Isothermal Transf. Diagram



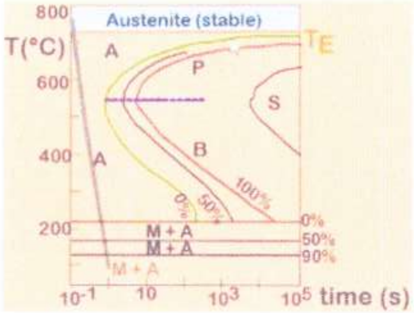


OTHER PRODUCTS: Fe-C SYSTEM (2)

- Martensite:
  - --γ(FCC) to Martensite (BCT)



- Isothermal Transf. Diagram



- γ to M transformation..
  - -- is rapid!
  - -- % transf. depends on T only.

COOLING EX: Fe-C SYSTEM (1)

- $C_o = C_{eutectoid}$
- Three histories...

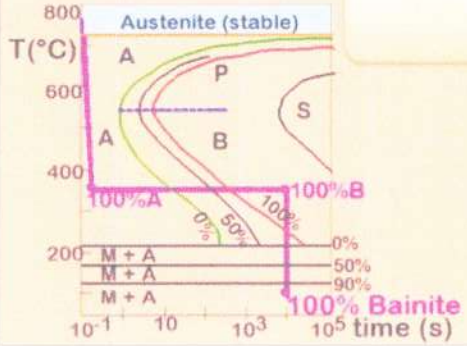
	Rapid cool to:	Hold for:	Rapid cool to:	Hold for:	Rapid cool to:
Example 1	350°C	10^4s	T_{room}		
Example 2	250°C	10^2s	T_{room}		
Example 3	650°C	20s	400°C	10^3s	T_{room}

COOLING EX: Fe-C SYSTEM (1)

- $C_o = C_{eutectoid}$
- Three histories...

	Rapid cool to:	Hold for:	Rapid cool to:	Hold for:	Rapid cool to:
Example 1	350°C	10^4s	T_{room}		

Case I

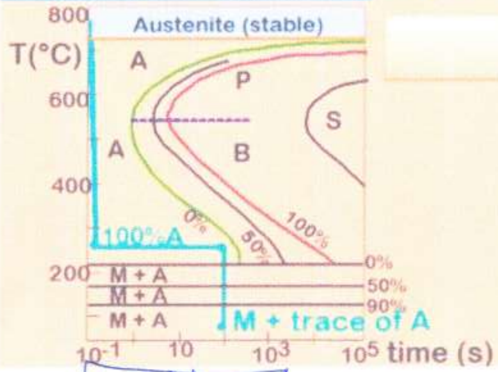


COOLING EX: Fe-C SYSTEM (2)

- $C_0 = C_{eutectoid}$
- Three histories...

Rapid cool to:	Hold for:	Rapid cool to:	Hold for:	Rapid cool to:
250°C	10^2s	T_{room}		

Example 2



benifits:-
→ We can use these properties to get martensite with Lower Cooling rates

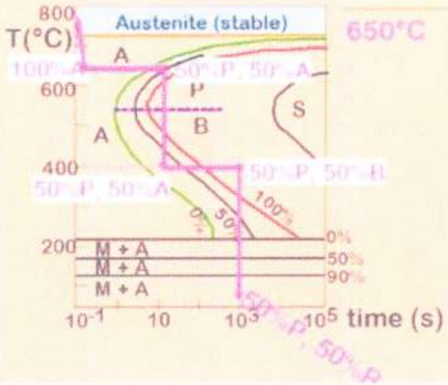
COOLING EX: Fe-C SYSTEM (3)

- $C_0 = C_{eutectoid}$
- Three histories...

Rapid cool to:	Hold for:	Rapid cool to:	Hold for:	Rapid cool to:
650°C	20s	400°C	10^3s	T_{room}

Example 3

Case III

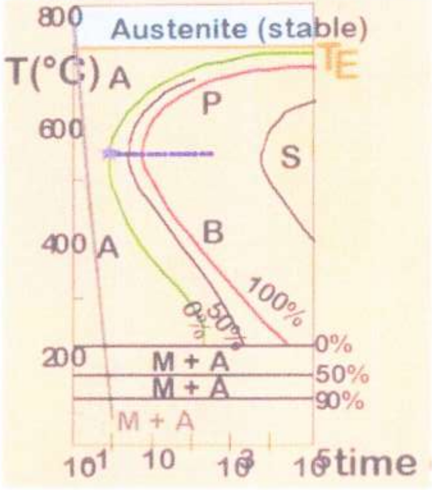


Critical cooling rates

Different alloys can affect the shape of the I-T diagrams:

1. An increase in carbon content moves the S-curve to the right (increases the time before transformation takes place).
2. Grain size also has an effect on hardenability (the property that determines the depth and distribution of hardness induced by quenching a ferrous alloy). Larger-grain carbon steels also take more time to transform. This also moves the S-curve to the right.
3. The addition of alloy to the steel also moves the S-curve to the right.

A plain low carbon steel cannot be hardened for practical purposes because the nose of the diagram is at or falls short of the zero time line, and it would be impossible to avoid cutting into it with the quenching or cooling curve (shown before).



★ Cooling rate that passes through the star (nose) is called the critical cooling rate

carbon content Ms temperature

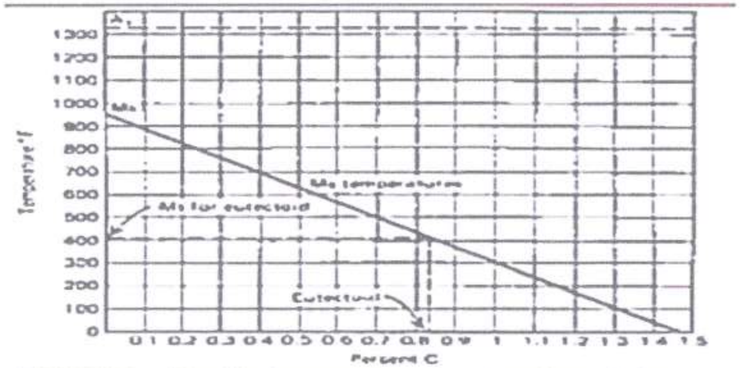


FIGURE 5. The Ms temperature is a function of the carbon content and will be further lowered when alloying elements are added. After finding the Ms temperature for steel containing a particular carbon content, subtract the following: 70 times the percentage of chromium, 70 times the percentage of manganese, 50 times the percentage of molybdenum, and 35 times the percentage of nickel (based on Fahrenheit temperatures).

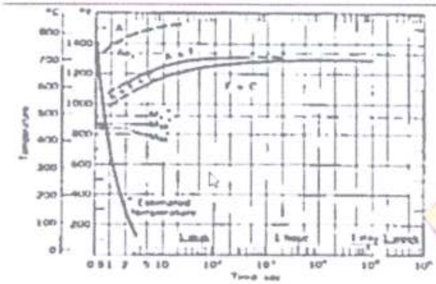


FIGURE 7. Brine quench cooling curve for SAE 1008 carbon steel (United States Steel Corporation)

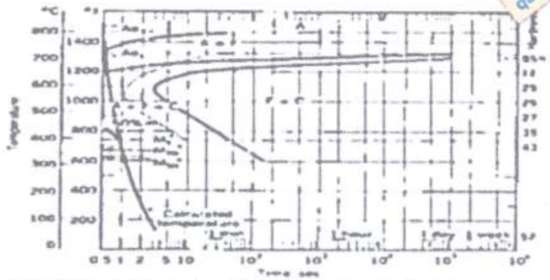
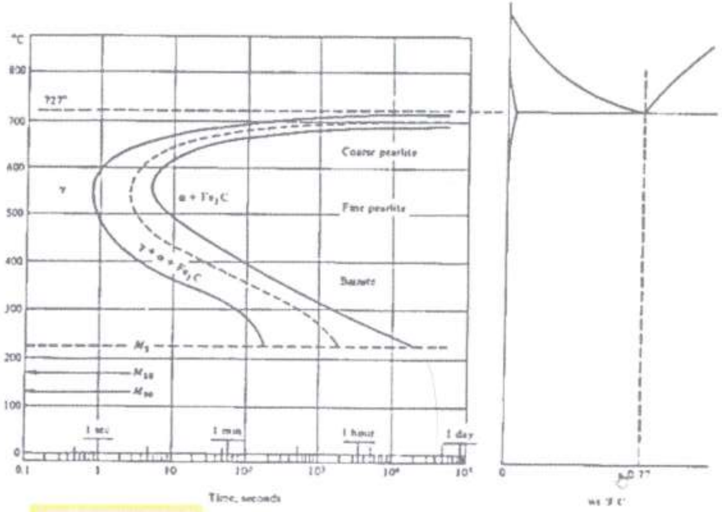


FIGURE 8. Brine quench cooling curve for 1034 modified Mn steel (United States Steel Corporation)

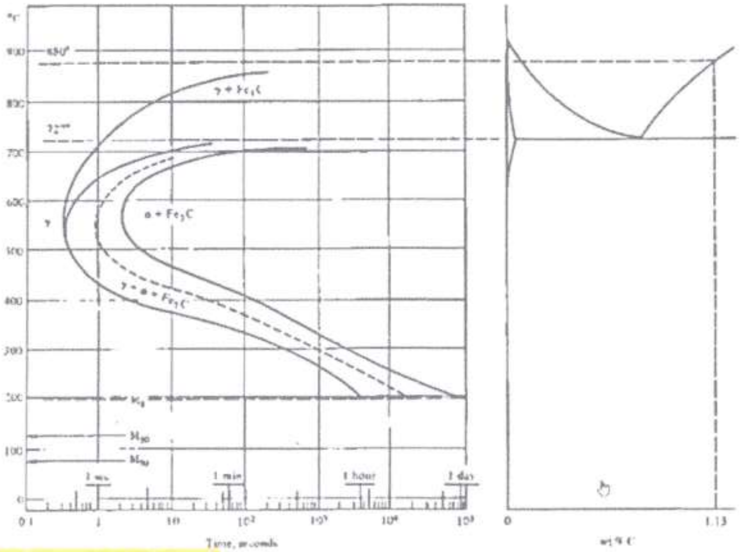
A plain low carbon steel cannot be hardened for practical purposes because the nose of the diagram is at or falls short of the zero time line, and it would be impossible to avoid cutting into it with the quenching or cooling curve (shown before).

Examples of isothermal heat treatment:

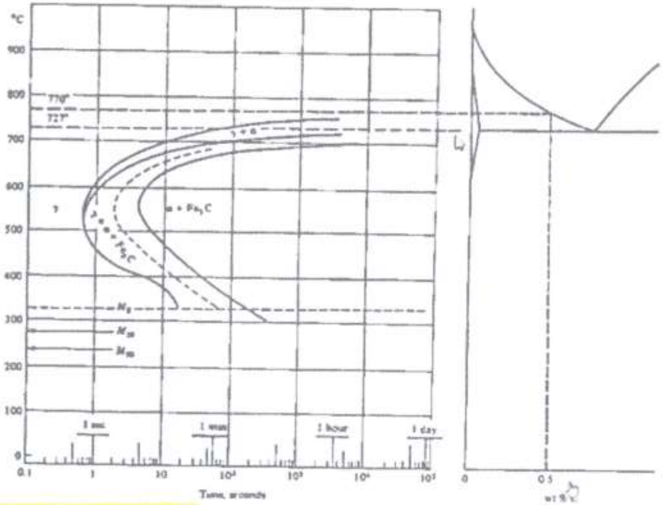
1. Eutectoid alloy of carbon steel
2. Hyper eutectoid alloy of carbon steel
3. Hypo eutectoid
4. Low carbon steel



Eutectoid alloy A more complete TTT diagram for eutectoid steel than was given in … The various stages of the time-independent (or diffusionless) martensitic transformation are shown as horizontal lines. M_s represents the start, M_{50} 50% transformation, and M_{90} 90% transformation. One hundred percent transformation to martensite is not complete until a final temperature (M_f) of − 46°C.



Hyper eutectoid alloy TTT diagram for a hypereutectoid composition (1.13 wt % C) compared to the Fe–Fe_3C phase diagram. Microstructural development for the slow cooling of this alloy was shown in Figure 5.5-4. (TTT diagram after *Atlas of Isothermal Transformation and Cooling Transformation Diagrams*, American Society for Metals, Metals Park, Ohio, 1977.)



Hypo eutectoid alloy

TTT diagram for a hypoeutectoid composition (0.5 wt % C) com-Fe$_3$C phase diagram. Microstructural development for the slow cooling of this alloy was shown in Figure 5.5-5. By comparing Figures 6.2-6, 6.2-9, and 6.2-10, one will note that the martensitic transformation occurs at decreasing temperatures with increasing carbon content in the region of the eutectoid composition. (TTT diagram after *Atlas of Isothermal Transformation and Cooling Transformation Diagrams*, American Society for Metals, Metals Park, Ohio, 1977.)

FIGURE 7. Brine quench cooling curve for SAE 1008 carbon steel (United States Steel Corporation)

A plain **low carbon steel** cannot be hardened for practical purposes because the nose of the diagram is at or falls short of the zero time line, and it would be impossible to avoid cutting into it with the quenching or cooling curve.

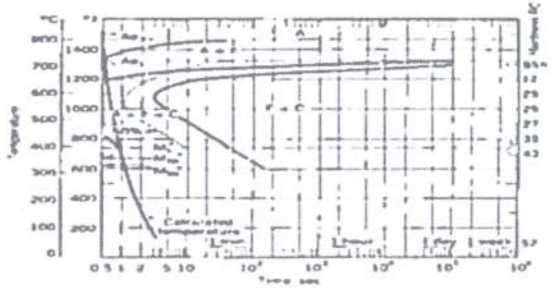


FIGURE 8. Brine quench cooling curve for 1034 modified Mn steel (United States Steel Corporation)

Isothermal heat treatment methods

Isothermal heat treatment methods similar to those of the conventional methods:

1. Isothermal annealing
2. Austempering
3. Martempering
4. Spherodizing

Isothermal heat treatment methods

1. *Isothermal annealing is done by quenching from above the critical range to the desired annealing temperature in the upper portion of the I-T diagram and holding at the anneal temperature for a length of time sufficient to produce complete transformation. This method produces a more uniform microstructure than conventional annealing, in which the steel is very slowly cooled.*

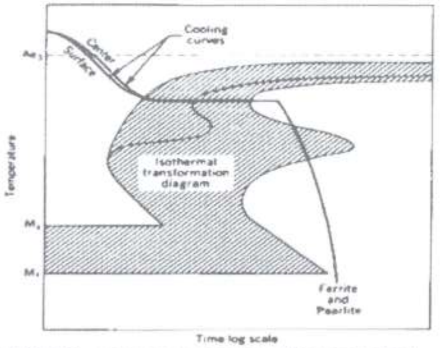


FIGURE 9. Isothermal annealing (Bethlehem Steel Corporation)

2. *Another method of hardening and tempering is a form of isothermal quenching called* ***austempering***, *in which a part is austenitized and quenched into a lead or salt bath held at a temperature of approximately 600°F (316°C) to produce a desired microstructure of lower bainite. It is held at this temperature for several hours until a complete transformation has taken place.*

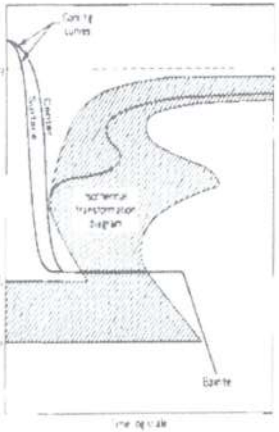


FIGURE 7. Austempering (Bethlehem Steel Corporation)

3. *Martempering*

the austenitized part is brought to slightly over the Ms temperature and held for a few minutes in order to equalize the interior and exterior temperatures to avoid stresses. Then the quench is continued to the Mf temperature, followed by conventional tempering.

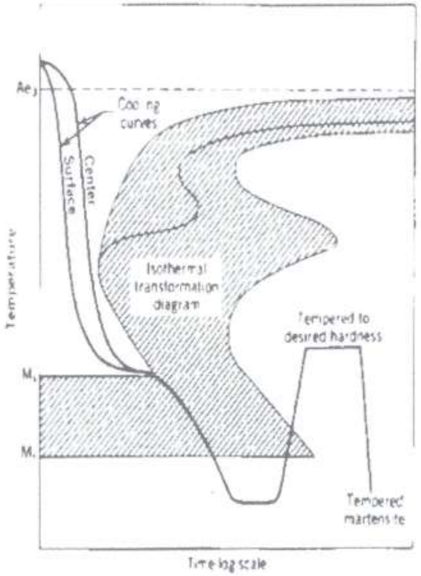
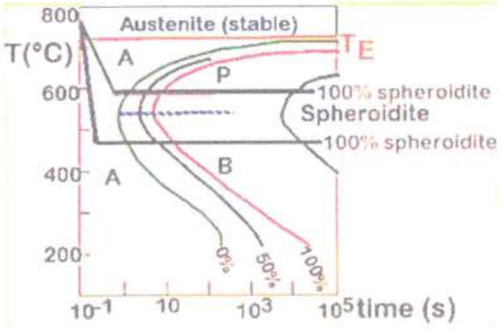
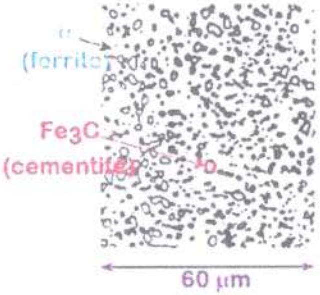


FIGURE 8. Martempering (Bethlehem Steel Corporation)

4. Spherodizing

- ***Spheroidite:***
  - *–α crystals with spherical Fe_3C*
  - *–diffusion dependent.*
  - *–heat bainite or pearlite for long times*
  - *–reduces interfacial area (driving force)*
- ***Isothermal Transf. Diagram***





Calculations using TTT curves:

Time calculation Sample Problem

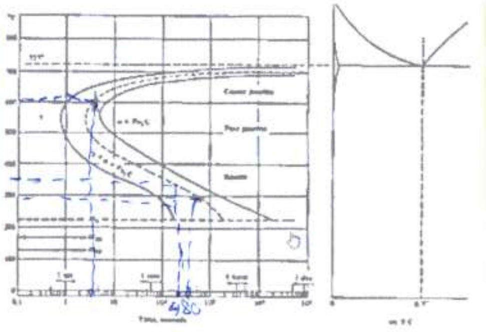
(a) **How long a time is required for austenite to transform to 50% pearlite at 600°C?**

(b) **How long a time is required for austenite to transform to 50% bainite at 300°C?**

✖ *Solution*

(a) This is a direct application of the Figure of the eutectoid composition isothermal diagram. The dotted line denotes the halfway-point in the γ → α + Fe3C transformation. At 600 ℃, the time to reach that line is ~ 3.5 s.

(b) At 300 ºC, the time is ~ 480 s or 8 min



Microstructural % calculation Sample Problem

(a) Calculate the microstructure of a 0.8 wt % C steel that has the following heat treatment: (i) instantly quenched from the γ region to 500°C, (ii) held for 5 s, and (iii) quenched instantly to 250°C.

(b) What will happen if the resulting microstructure is held for 1 day at 250°C and then cooled to room temperature?

(c) What will happen if the resulting microstructure from (a) is quenched directly to room temperature?

(d) Sketch the various thermal histories.

Solution

(a) By having ideally fast quenches, we can answer this precisely in terms of the Figure of the eutectoid alloy. The first two parts of the heat treatment lead to ~70 percent transformation to fine pearlite. The final quench will retain this state:

$$30\%\ \gamma + 70\%\ \text{fine pearlite}\ (\alpha + Fe_3C)$$

(b) The pearlite remains stable, but the retained γ will have time to transform to bainite, giving a final state

$$30\%\ \text{bainite}\ (\alpha + Fe_3C) + 70\%\ \text{fine pearlite}\ (\alpha + Fe_3C)$$

(c) Again, the pearlite remains stable, but most of the retained γ will become unstable. For this case, we must consider the martensitic transformation data in Figure (eutectoid). The resulting microstructure will be

$$70\%\ \text{fine pearlite}\ (\alpha + Fe_3C) + \text{about}\ 30\%\ \text{martensite}$$

(Because the martensitic transformation is not complete until -46°C, a small amount of untransformed γ will remain at room temperature

---

Quench rate *calculation Sample Problem*

Estimate the quench rate needed to avoid pearlite formation in:

(a) 0.5 wt % C steel.

(b) 0.77 wt % C steel.

(c) 1.13 wt % C steel.

- *Solution*

In each case, we are looking at the rate of temperature drop needed to avoid the pearlite "knee":

Note of caution. This is a use of an isothermal transformation diagram to illustrate a continuous cooling process. **Precise calculation would require a true continuous cooling transformation curve.**

(a) From Figure (hypo alloy) for a 0.5 wt % C steel, we must quench from the austenite boundary (770°C) to ~520°C in about 0.6 s giving

$$\Delta T/t = [(770 - 520)°C]/\ 0.6\ s = 420°C/s$$

(b) From Figure (euectoid alloy) for a 0.77 wt % C steel, we quench from the eutectoid temperature (727°C) to ~550°C in about 0.7 s, giving

$$[(727 - 550)°C]/0.7s = 250°C/s$$

(c) From Figure (hyper alloy)for a 1.13 wt % C steel, we quench from the austenite boundary(880°C) to ~550°C in about 3.5 s, giving

$$[(880 - 550)°C]/0.35\ s = 940°C/s$$

More examples:

- **Calculate** the time required for austempering at 5°C above the Ms temperature for 0.5 wt % C steel.

- **Solution**

(a) Figure (Hypo) for 0.5 wt % C steel indicates that complete bainite formation will have occurred 5°C above Ms by

about 180 s x 1 m/60 s = 3 min

Continuous cooling curves

There are two main types of transformation diagram that are helpful in selecting the optimum steel and processing route to achieve a given set of properties. These are

1. time-temperature transformation (**TTT**) and
2. continuous cooling transformation (**CCT**) diagrams.

CCT diagrams are generally more appropriate for engineering applications as components are cooled (air cooled, furnace cooled, quenched etc.) from a processing temperature as this is more economic than transferring to a separate furnace for an isothermal treatment.

Definitions

Time-temperature transformation (TTT) diagrams measure the rate of transformation at a constant temperature. In other words a sample is austenitised and then cooled rapidly to a lower temperature and held at that temperature whilst the rate of transformation is measured, for example by dilatometry. Obviously a large number of experiments is required to build up a complete TTT diagram.

Continuous cooling transformation (CCT) diagrams measure the extent of transformation as a function of time for a continuously decreasing temperature. In other words a sample is austenitised and then cooled at a predetermined rate and the degree of transformation is measured, for example by dilatometry. Obviously a large number of experiments is required to build up a complete CCT diagram.

Comparison of the TTT with CCT diagrams

1. *Delay in the transformation starts in CCT*
2. *Delay in the transformation ends in CCT*
3. *Bainite will not form in CCT*
4. *Change in the critical rate of martensite transformation (nose)in CCT*
5. *The transformation in CCT curves ceases at the point of intersection with TTT*

For eutectoid plain carbon steel, the Ms, M (50%), M(90%) are identical both TTT and CCT curves

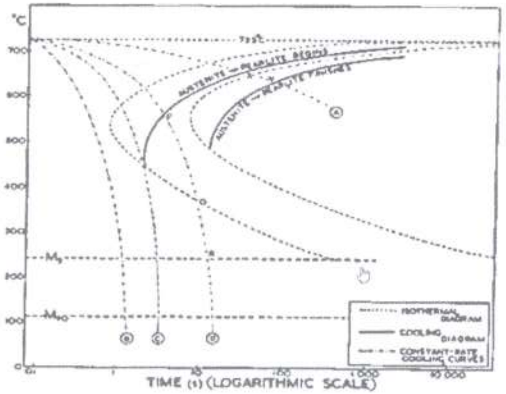
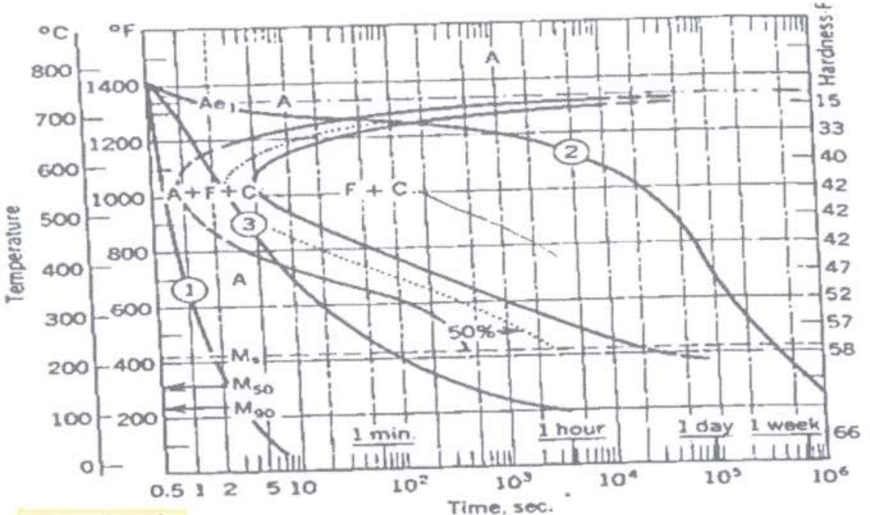


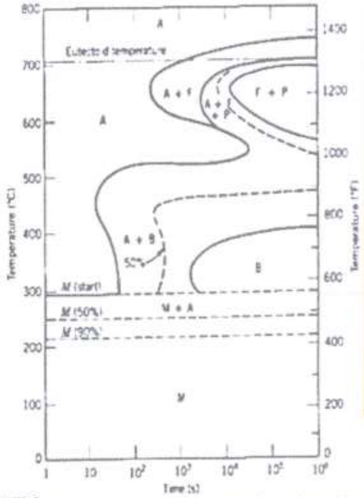
Fig. 12.9 The relationship between TTT curves and curves representing continuous cooling.



Example with cooling curves

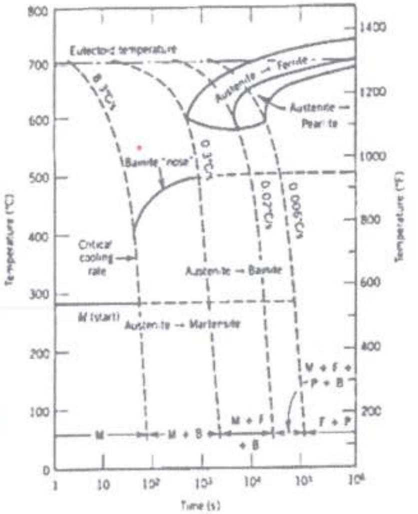
Cooling curves on an I-T diagram for eutectoid steel. Line 1 shows the quench for undercooling to produce martensite; line 2 shows an annealing curve; line 3 is a normalizing curve. (United States Steel Corporation)

Some useful information about TTT, CCT Curves



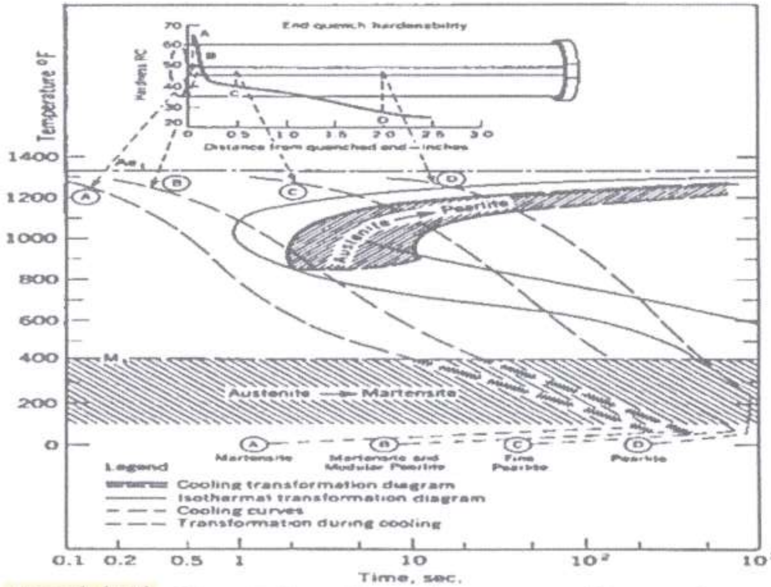
TTT Curve Isothermal transformation diagram for an alloy steel (type 4340): A, austenite; B, bainite; P, pearlite; M, martensite. (Adapted from H. Boyer, Editor, *Atlas of Isothermal Transformation and Cooling Transformation Diagrams*, American Society for Metals, 1977, p. 181.)

Note that there is a Bainite in CCT curve of alloy steel



CCT Curve Continuous cooling transformation diagram for an alloy steel (type 4340) and several superimposed cooling curves demonstrating dependence of the final microstructure of this alloy on the transformations that occur during cooling. (Adapted from H. E. McGannon, Editor, *The Making, Shaping and Treating of Steel*, 9th edition, United States Steel Corporation, Pittsburgh, 1971, p. 1096.)

TTT & CCT CURVES FOR THE 4340 ALLOY STEEL (DIFFERENT CURVES FOR THE SAME ALLOY)



Example (CCT) **Correlation of continuous cooling and isothermal transformation diagrams with end-quench hardenability test data for eutectoid carbon steel. (United States Steel Corporation)**

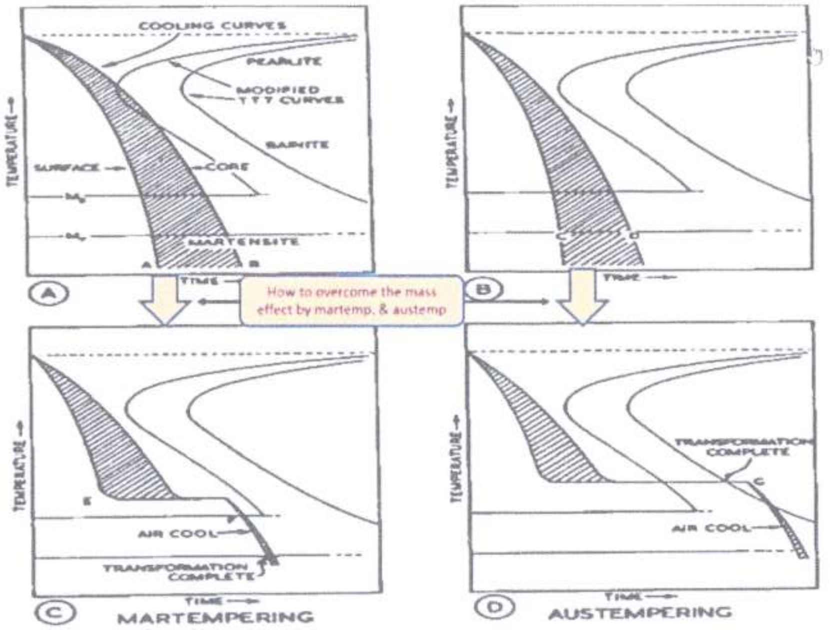
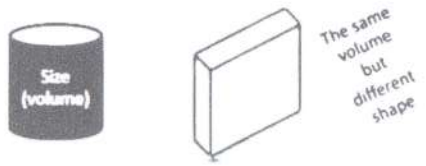


Fig. 12.11 (A) and (B) illustrate the effects of mass during normal quenching. (C) and (D) show how these effects may be largely overcome in martempering and austempering.

The correlation between Factors influence the succefullness of the heat treatment process and I-T Curves

1. The quenching media (includes the severity of the media). The severity from high to low can be ranked as follows: 5% caustic soda, 20% brine, cold water, warm water, mineral oil, animal oil, vegetable oil, air, insulating material or furnace.
2. The composition of the alloy (shifting of critical cooling rate to the right)
3. The size and shape of the specimen (Figure below)



Heat treatment of alloy steels (case studies)

1. Water-hardening tool steel- SAE1095 (W1)

W1 steel should be used only for smaller parts and tools but not very thick sections since this tool steel is subject to cracking when unevenly quenched.

1. The part should be slowly heated to between (787.7 to 815.5°C) and soak about 15 minutes per inch of thickness.
2. Then Quenched in clean water or preferably "brine solution, which prevents bubbles from forming and uneven quenching. The coolant should be between (15.5 and 26.6°C).
3. When, the tool is down to about (148.8°C), it should be removed from the quench and air cooled to where the tool is not hot but still quite warm to the touch.

Note that:

Water-hardening steels may be tempered with a torch or hot plate or in a furnace; in any case, tempering should be done before the piece cools to room temperature

2. Oil-hardening tool steel- AISI type 06

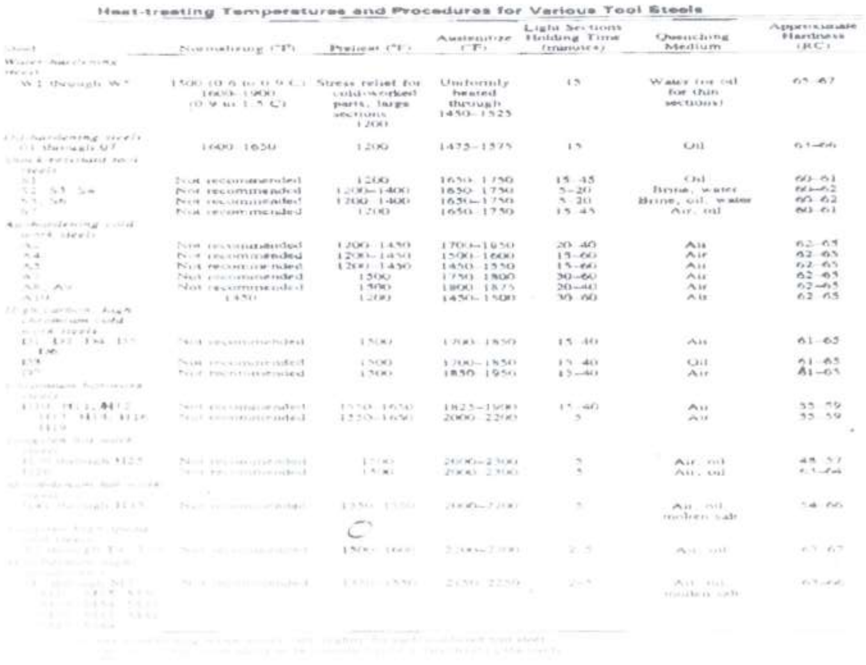
The metal should be in proper condition to be hardened, that is, normalized and holes plugged and covered with non scaling compound or buried in cast iron chips.

1. Large sections should be brought up to (648.8°C) slowly, but small parts may be put directly in a (648.8°C) furnace. It should be thoroughly heated through at this temperature, then raised to (787.7°C) or up to (801.6 to 815.5°C) for larger sections.
2. ThenThe piece should be thoroughly soaked (about 1 hour per inch of a least transverse cross section).
3. The part should then be removed from the furnace and immediately quenched in agitated oil at (43 to 54°C).
4. The part should not be kept in the oil until completely cold, but should be taken directly from the quench when it is about (93°C) and placed in the tempering furnace. The time in the tempering furnace should be about the same as that for hardening.

The hardness of this steel when tempered to (204.4°C) should be about RC 62 and the hardness when tempered to (315.5°C) would be about RC 58. Hardening procedures and tempering temperatures plus the resultant hardness may be

3. Air-hardening tool steel-AISI type A10

1. Air-hardening steel should be brought to heat slowly if it is a thick section and preheated at 1200°F (648.8°C) until soaked uniformly through.
2. It can then be brought to the hardening temperature of l450°F (787.7°C) for small parts to 1500°F (815.5°C) for large pieces.
3. The tool steel should be soaked so it is an even temperature throughout. The rule of thumb of soaking 1 hour per inch of section applies to this steel.
4. The quenching medium is still air (a cold breeze may crack it), so the piece is simply removed from the furnace and placed on a brick to cool. The hardness, as quenched, should be RC 60 to 62.
5. As soon as it is cool enough to touch, but still warm, it should be placed in a tempering oven or furnace for 1 hour per inch of section. The hardness would be reduced to about RC 60 at 500°F (260°C) and about RC 57 at 700°F (371°C)



Heat-treating Temperatures and Procedures for Various Tool Steels

Steel	Normalizing (°F)	Preheat (°F)	Austenitize (°F)	Light Sections Holding Time (minutes)	Quenching Medium	Approximate Hardness (RC)
Water-hardening steels						
W1 through W7	1500 (0.6 to 0.9 C) 1600–1900 (0.9 to 1.5 C)	Stress relief for cold-worked parts, large sections 1200	Uniformly heated through 1450–1525	15	Water (or oil for thin sections)	65–67
Oil-hardening steels O1 through O7	1600–1650	1200	1475–1575	15	Oil	63–66
Shock-resistant tool steels						
S1	Not recommended	1200	1650–1750	15–45	Oil	60–61
S2, S3, S4	Not recommended	1200–1400	1650–1750	5–20	Brine, water	60–62
S5, S6	Not recommended	1200–1400	1650–1750	5–20	Brine, oil, water	60–62
S7	Not recommended	1200	1650–1750	15–45	Air, oil	60–61
Air-hardening cold work steels						
A2	Not recommended	1200–1450	1700–1850	20–40	Air	62–65
A4	Not recommended	1200–1450	1500–1600	15–60	Air	62–65
A5	Not recommended	1200–1450	1450–1550	15–60	Air	62–65
A7	Not recommended	1500	1750–1800	30–60	Air	62–65
A8, A9	Not recommended	1500	1800–1875	20–40	Air	62–65
A10	1450	1200	1450–1500	30–60	Air	62–65
High-carbon, high-chromium cold work steels						
D1, D2, D4, D5, D6	Not recommended	1500	1700–1850	15–40	Air	61–65
D3	Not recommended	1500	1700–1850	15–40	Oil	61–65
D7	Not recommended	1500	1850–1950	15–40	Air	61–65
Chromium hot-work steels						
H10, H11, H12	Not recommended	1550–1650	1825–1900	15–40	Air	55–59
H13, H14, H16, H19	Not recommended	1550–1650	2000–2200	5	Air	55–59
Tungsten hot-work steels						
H20 through H25	Not recommended	1500	2000–2300	5	Air, oil	48–57
H26	Not recommended	1500	2000–2300	5	Air, oil	63–64
Molybdenum hot-work steels						
H41 through H43	Not recommended	1350–1550	2000–2200	5	Air, oil, molten salt	54–66
Tungsten high-speed tool steels						
T1 through T4, T15	Not recommended	1500–1600	2200–2300	2–5	Air, oil	63–67
Molybdenum high-speed steels						
M1 through M7, [illegible]	Not recommended	1350–1550	2050–2250	2–5	Air, oil, molten salt	63–66

[illegible]

Quenching describes the sudden immersion of a heated metal into cold water or oil. It is used to make the metal very hard.

Quenching process is typically achieved by cooling at a comparatively high rate. This is done to avoid problems like internal microstructure that are not desired, ensuring uniform mechanical property, minimal residual stress, warpage avoidance.

Cooling typically takes place in three distinct stages, each with a distinct characteristics:

1. *Vapor phase*
2. *Boiling phase*
3. *Convection phase*

Types of quenching

1. **LIQUID QUENCHING**
   - ***A. still-bath***
   - ***B. flush quenching***
2. **Dry quenching**
3. **Polymer quenching**

In still-bath quenching, you cool the metal in a tank of liquid. The only movement of the liquid is that caused by the movement of the hot metal, as it is being quenched

In flush quenching, the liquid is sprayed onto the surface and into every cavity of the part at the same time to ensure uniform cooling.

Liquid quenching media:

Water

Water can be used to quench some forms of steel, but does not produce good results with tool or other alloy steels. Water absorbs large quantities of atmospheric gases, and when a hot piece of metal is quenched, these gases have a tendency to form bubbles on the surface of the metal. These bubbles tend to collect in holes or recesses and can cause soft spots that later lead to cracking or warping.

Brine

Brine is the result of dissolving common rock salt in water. This mixture reduces the absorption of atmospheric gases that, in turn, reduces the amount of bubbles. As a result, brine wets the metal surface and cools it more rapidly than water. In addition to rapid and uniform cooling, the brine removes a large percentage of any scale that may be present.

The brine solution should contain from 7% to 10% salt by weight or three-fourths pound of salt for each gallon of water. The correct temperature range for a brine solution is 65°F to 100°F.

Low-alloy and carbon steels can be quenched in brine solutions; however, the rapid cooling rate of brine can cause cracking or stress in high-carbon or low-alloy steels that are uneven in cross section. Because of the corrosive action of salt on nonferrous metals, these metals are not quenched in brine.

Oil

Oil is classed as an intermediate quench. It has a slower cooling rate than brine or water and a faster rate than air. The quenching oil temperature should be kept within a range of 80°F to 150°F. Nonferrous metals are not routinely quenched in oil unless specifications call for oil quenching.

Oil composition:

1-Petroleum –derived quench oils.
2. Quenching oils derived from fats

Quench oil must possess several important properties:

- *Acceptable flash & fire point*
- *Low sludge formation*
- *Non staining of parts*
- *Appropriate heat removal properties*

Quench oil selection

The following criteria has been proposed for the selection of a quenching oils:

1. *An oil with a relatively slow cooling rates (a conventional oil)should be used For products with thick cross sections*
2. *Depending on the quenching methods an agitation of the oil, the oil temperatures should be adjusted to give a viscosity of 5 to 15 (N.Sec/square meter)*
3. *The minimum flash point of the oil should be 90°C above the oil temperatures being used*

---

2. Dry quenching

This type of quenching uses materials other than liquids. In most cases, this method is used only to slow the rate of cooling to prevent warping or cracking.

Air

Air quenching is used for cooling some highly-alloyed steels.

When you use still air, each tool or part should be placed on a suitable rack so the air can reach all sections of the piece.

Although nonferrous metals are usually quenched in water, pieces that are too large to fit into the quench tank can be cooled with forced-air drafts; however, an air quench should be used for nonferrous metal only when the part will not be subjected to severe corrosion conditions and the required strength and other physical properties can be developed by a mild quench.

Solids

The solids used for cooling steel parts include cast iron chips, lime, sand, and ashes. Solids are generally used to slow the rate of cooling; for example, a cast-iron part can be placed in a lime box after welding to prevent cracking and warping. All solids must be free of moisture to prevent uneven cooling

---

3. Polymer quenching

Polymer Quenchant Maintenance Concerns:

1. Contamination

the most common causes of non-uniformity are:

- ***Quenching medium contamination***
- ***Foaming***
- ***Formation of Carbon and sludge on the surface***
- ***salts***

---

2. Polymer Concentration

heat transfer during quenching is controlled by both:

1. ***viscosity***
2. ***thickness of the polymer film.***

The viscosity of the polymer is determined by the selection of the particular polymer used to formulate the quenchant.

Thickness of the polymer film is controlled by concentration of the quenchant

---

3. Degradation

Polymer degradation which results in a reduction in the molecular weight (size) of the polymer may potentially occur by: one of two processes.

1. ***Mechano-degradation***
2. ***oxidative/thermal degradation***

Notes to be taken into consideration for polymer quenching

1. *A closed and recirculating quench system should be used.*
2. *The temperature controls for heating and cooling should be employed.*
3. *It is critically important that heat should be removed from the part at a properly controlled and reproducible rate.*
4. *The volume of the system should be a minimum of five times the maximum volume rate of flow that the quenchant is pumped per minute. For example, if the flow rate is 400 l/min, then the volume of the tank should be 2000.*

5. *The quenchant must be kept clean. Solid contamination not only produces non-uniform at the hot metal interface but it also plugs quench holes.*
6. *Low concentrations (~5%) of the quenchant minimize the potential for cracking by facilitating more uniform surface wetting than achievable with water itself.*
7. *If the hardness pattern extends into a shaft, cracking potential can be minimized by immersion quenching. If spray quenching is used, an auxiliary spray stream is required for the end face of the shaft. Non-uniform quenching will lead to quench cracking*

HEAT TREATMENT FURNACES

Definition

Heat treating furnaces are essentially heating chambers, i.e., a refractory vessel which holds the steel stock as well the heat. The furnace chamber is heated with some source of heat. The supply of heat must be regulated depending on the requirement. More heat is needed during the heating period, but almost a constant heat is required when the furnace has attained the required temperature and is to be maintained at that temperature.

The heat has to be supplied to the whole of the properly designed furnace in a way that the temperature is constant everywhere, or at the places where the charge is being kept otherwise some parts may get under heated, or overheated. The doors, or openings are kept as small sized as possible to reduce the heat losses.

Tempering and low temperature furnaces may require provisions for forced air or atmosphere circulation.

The carburized parts may be quenched inside the furnace itself.

General Requirements for Furnaces

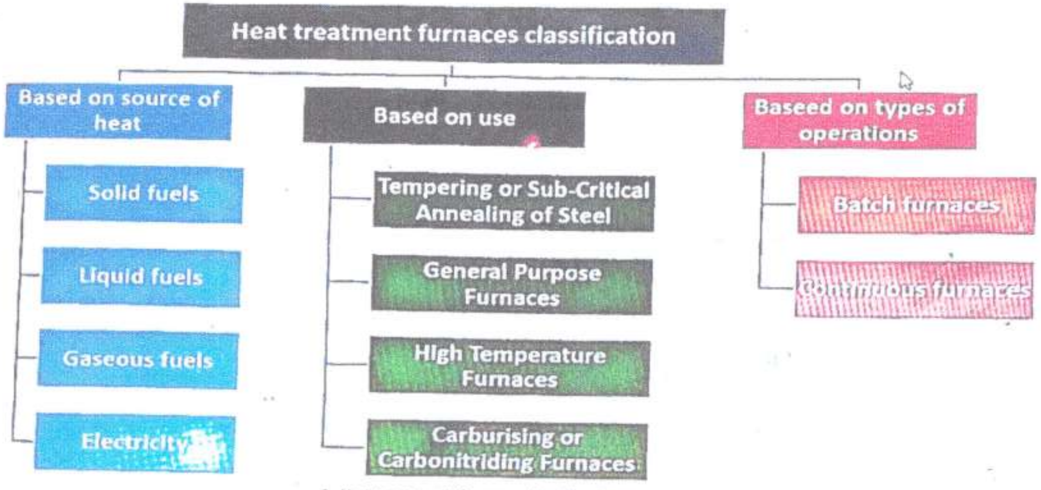
1. Heating source.
2. Conservation of heat generated.
3. Constant temperature inside it.
4. Openings.
5. Controlled atmosphere (necessary).
6. Structure of the furnace must withstand high temperatures and hard conditions.

Auxiliary parts: ***Temperature controller, Temperature recording system***

Important factors: ***soaking time & soaking temp***

Sizes: ***small to very large***

3.TYPES OF HEAT TREATMENT FURNACES



Heat treatment furnaces classification

Based on source of heat
- Solid fuels
- Liquid fuels
- Gaseous fuels
- Electricity

Based on use
- Tempering or Sub-Critical Annealing of Steel
- General Purpose Furnaces
- High Temperature Furnaces
- Carburising or Carbonitriding Furnaces

Baseed on types of operations
- Batch furnaces
- Continuous furnaces

1- Heat treatment furnaces classification

CONSIDERATIONS FOR CHOOSING FURNACES

1. The purpose for which type of material needs to be heated.
2. Source of heat and the Nature of heat transfer to the material.
3. Heating by batch or continuously and the method of handling materials.
4. Type of heat recovery (an energy recovery system that recovers normally wasted heat; it can have great savings on energy bills).

> For further detailed information about Heat Treatment furnaces you can refer to literature Here, we will give some useful information that may help in understanding what may happen during the process of heat treatment.

Disadvantages of small electric furnaces:

Oxidation at high temperature which leads to the decarburization of the surface of the metal.

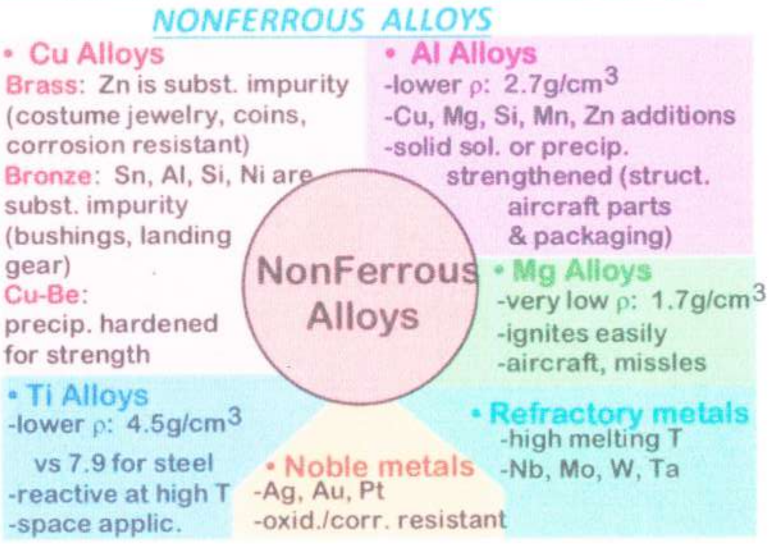
Overcoming this problem:

1. *Inert gas environment*
2. *Wrapping the metal in stainless steel foil*
3. *Packing In cast iron chips*
4. *Wrapping with a paste of boric acid and water*

Common causes of quench cracks:

1. **Overheating during the austenizing cycle (fine grains become coarse)**
2. **Improper selection of the quenching medium (using water or brine instead of oil for an oil hardening steels)**
3. **Improper selection of steel**
4. **Time delay between quenching and tempering**
5. **Improper design (sharp edges, holes,...etc)**
6. **Improper angle of the work into the quenching medium.**

Heat treatment of non ferrous alloys



NONFERROUS ALLOYS

- **Cu Alloys**

Brass: Zn is subst. impurity (costume jewelry, coins, corrosion resistant)

Bronze: Sn, Al, Si, Ni are subst. impurity (bushings, landing gear)

Cu-Be: precip. hardened for strength

- **Al Alloys**

-lower ρ: 2.7g/cm^3
-Cu, Mg, Si, Mn, Zn additions
-solid sol. or precip. strengthened (struct. aircraft parts & packaging)

NonFerrous Alloys

- **Mg Alloys**

-very low ρ: 1.7g/cm^3
-ignites easily
-aircraft, missles

- **Ti Alloys**

-lower ρ: 4.5g/cm^3 vs 7.9 for steel
-reactive at high T
-space applic.

- **Noble metals**

-Ag, Au, Pt
-oxid./corr. resistant

- **Refractory metals**

-high melting T
-Nb, Mo, W, Ta

Safety

When heat treating, always wear a face shield, leather, gloves, and long sleeves. *There is a definite hazard to the face and eys when cooling the tool steel by quenching, that is, submerging it in oil. The oil, hot from the steel, tends to fly upward, so you should stand to one side of the oil tank and not lean over it.*

Always work in pairs during heat treatment. *One person can open and close the furnace door while the other handles the hot part. The heat-treated part should be positioned in the furnace so it can be conveniently removed. This will prevent the heat treater from dropping hot parts and help to ensure successful heat treatment. Atmospheric furnaces should never be opened until the gas supply is turned off. Failure to do so could result in an explosion.*

Safety Note. *Very toxic fumes are present when parts are being carburized with compounds containing potassium cyanide. These cyanogen compounds are highly poisonous and every precaution should be taken when using them. Kasenite®, a trade name for a carburizing compound that is not toxic, is often found in school shops and machine shops.*

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Main methods of the heat treatment of non ferrous:

1. *Solution heat treatment*
2. *Precipitation heat treatment (aging)*

Requisite features of the phase diagram for precipitation hardening:

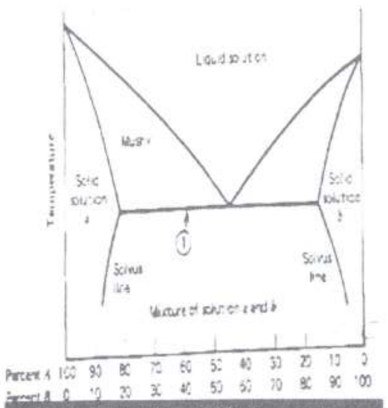
1. *An appreciable maximum solubility of one component in the other.*
2. *Solubility limit that rapidly decreases in concentration of the major component with temperature reduction*

Main methods of the heat treatment of non ferrous metals and alloys

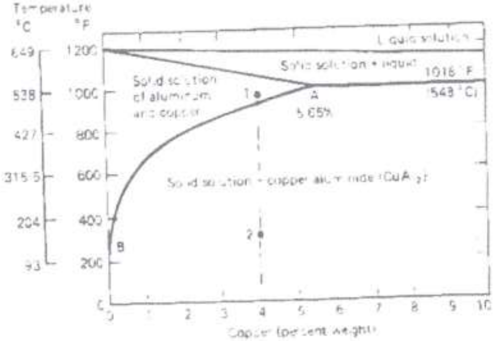
1. Solution heat treatment (natural aging)
2. Precipitation heat treatment (artificial aging)

Requisite features of the phase diagram for precipitation hardening

1. An appreciable maximum solubility of one component in the other.
2. Solubility limit that rapidly decreases in concentration of the major component with temperature reduction



General

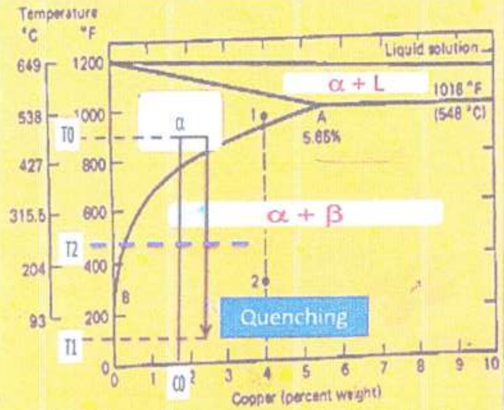


Example Aluminum-copper equilibrium diagram showing the aluminum-rich end. Line *A-B* represents the increase in solubility of copper with increasing temperature in aluminum in the solid state.

Solution heat treatment procedure (Natural aging)

1. Heating the alloy of composition C0 to Temperature T0 to form the single phase α.
2. Give enough time till complete solution of B in A.
3. Rapid cooling (quenching to temp. T1) to prevent the formation of β phase.
4. α supersaturated with B (Non equilibrium structure, soft & weak alloy).

(This structure can be retained at this temperature [room temp. or T1] for relatively long periods)



Aluminum-copper equilibrium diagram showing the aluminum-rich end. Line *A-B* represents the increase in solubility of copper with increasing temperature in aluminum in the solid state.

PRECIPITATION HARDENING (Artificial aging)

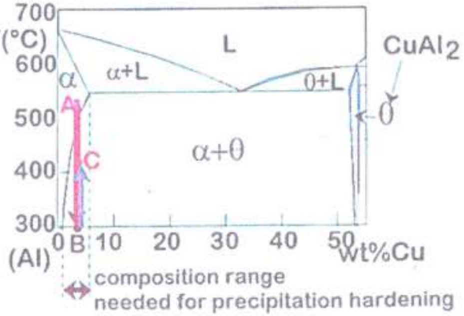
Example : Al-Cu system

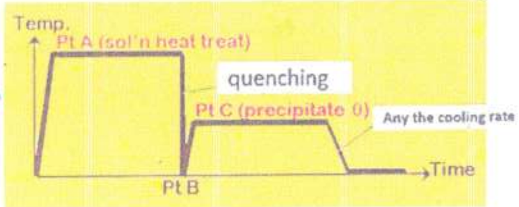
- *Procedure:*

  –*Pt A: solution heat treat (get α solid solution)*
  –*Pt B: quench to room temp.*
  –*Pt C: reheat to nucleate*

  small θ crystals within α crystals.

- *Other precipitation systems:*
  - *Cu-Be*
  - *Cu-Sn*
  - *Mg-Al*





Solution Heat Treatment with Aging Times and Temperatures for Some Commercial Hardenable Aluminum Alloys

		Soaking Time for Various Thicknesses (Minutes)			
Designation	Soaking Temperature (°F)	Up to 0.032 in.	Over 0.032 to 0.125 in.	Over 0.125 to 0.025 in.	Ove 0.25 in.
2014-T6	925–950	20	20	30	60
2017	925–950	20	20	30	60
2117	890–950	20	20	30	60
2024	910–930	30	30	40	60
6061-T6	960–1010	20	30	40	60
7075	860–960	25	30	40	60

Note. Soaking time begins after the part has reached temperature.

Designation	Aging Temperature (°F)	Aging Time (Hou
2014-T6	345–355	2 to 4
	355–375	½ to 1
2017	Room temperature	96
2117	Room temperature	96
2024	Room temperature	96
6061-T6	315–325	50 to 100
	345–355	8 to 10
7075	245–255	24
	315–325	1 to 2

Useful Information

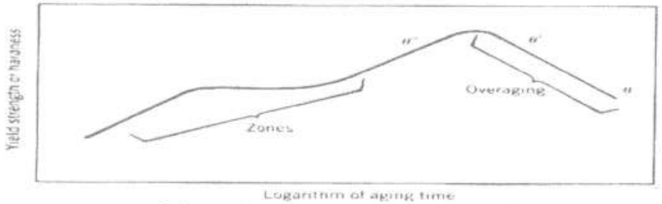
1. the copper when brought to a supersaturated condition in the aluminum, will precipitate very fine particles of copper aluminide at the grain boundaries and along crystal planes, producing strains in the aluminum. This process is called aging or precipitation heat treatment .

2. Artificial aging speeds up this process and also increases strength but lowers corrosion resistance in some alloys such as 2024. Artificial aging consists of heating the solution heat-treated and quenched part for several hours at 250 to 360°F (121 to 182°C), depending on the alloy, and then cooling the part to below 100°F (38°C). This is sometimes repeated before cooling to room temperature, which is called interrupted heat treatment.

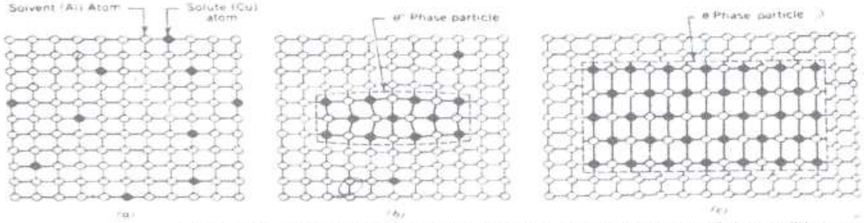
3. Overaging time or temperatures that are too high cause a loss of strength and corrosion resistance since this enlarges the copper aluminide particles. However, even with normal aging, corrosion resistance is lower in these hardenable alloys than in pure aluminum.

4. Cold working of aluminum is often done immediately after solution heat treatment and before aging begins. This process assures an even greater hardness and tensile strength of the aged part. An example of this procedure is in the use of aluminum alloy rivets for aircraft. The rivets must be used before they become aged or the heads will split as a result of cold work when riveting. Table 1 shows solution heat treatment and aging times for some aluminum alloys.

Hardening and strengthening mechanism



Schematic diagram showing tensile strength and hardness as a function of the logarithm of aging time at constant temperature during the precipitation heat treatment.

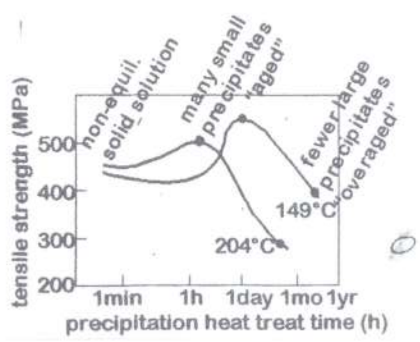


11.15 Schematic depiction of several stages in the formation of the equilibrium precipitate (θ) phase. (a) A supersaturated α solid solution. (b) A transition, θ'', precipitate phase. (c) The equilibrium θ phase, within the α matrix phase. Actual phase particle sizes are much larger than shown here.

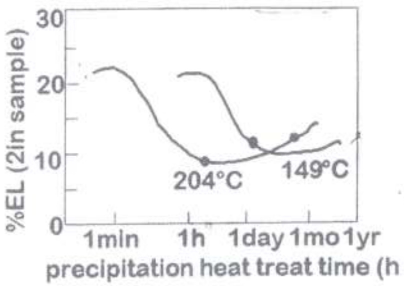
The effect of precipitation H.T. on Tensile strength and %Elongation

- *2014 Al Alloy:*

- **TS peaks with precipitation time.**
- **Increasing T (below solvus line) accelerates process.**



- **%EL reaches minimum with precipitation time.**



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Heat treatment of other non ferrous alloys

HEAT TREATING MAGNESIUM ALLOYS

Some magnesium alloys can be solution heat treated and aged, when proper heat-treating procedures are used. Extensive study and experience are required to heat treat this material safely. Manufacturers' catalogs and reference books such as the Metals Handbook from the American Society for Metals may be consulted for heat-treating procedures.

HEAT TREATING NICKEL AND NICKEL ALLOYS

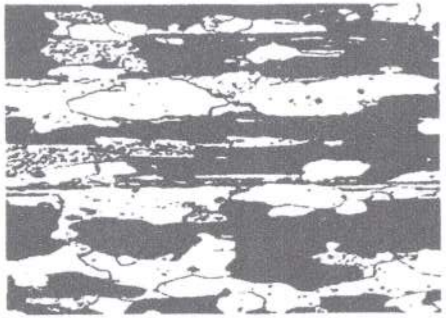
Nickel and its alloys may be annealed, stress relieved, and, in some cases, solution heat treated and aged. Among the hardenable nickel alloys are permanickel 300, duranickel 301, monel 501, inconel 718, and hastelloy R-235.

Solution temperatures for these alloys are from 1800 to 2000°F (982 to 1093°C), except for monel 501, which is 1525°F (829°C).

Aging temperature for permanickel is about 900°F (482°C).

The other hard-enable alloys must be aged for 16 hours at 1100°F (593°C) and then at 1000°F (538°C) for 6 hours, followed by 8 hours at 900°F (482°C), and air cooled.

Annealing is carried out by heating to a predetermined temperature for a period of time and then quenching in water. As with most metals, a scale may be formed at high temperatures. This can be controlled by using a carbon-rich furnace atmosphere or by bright annealing in a closed container with an inert gas.



IGURE 8b. Recrystallization of the same cold-worked luminum was produced by stress relief anneal (100×). ly permission, from *Metals Handbook*, Volume 7, opyright American Society for Metals, 1972)

HEAT TREATING COPPER ALLOYS

Some copper alloys may be hardened by solution heat treatment and precipitation (aging) and then can be stress relieved or annealed. The important copper alloys that can be age hardened by precipitation are beryllium copper, aluminum bronze, copper-nickel-silicon, copper-nickel-phosphorus, chromium copper, and zirconium copper.

Aluminum bronzes containing more than 10 percent aluminum are hardened by quenching from a high temperature of about 1200°F (649°C) to produce a martensitic type of structure similar to that of hardened steel. This is followed by tempering at a lower temperature.

Beryllium copper and other hardenable alloys are solution heat treated and precipitation hardened. Beryllium copper containing nickel or cobalt is solution treated at 1425 to 1475°F (774 to 802°C) for 1 to 3 hours and quenched in water. Aging time is from 2 to 3 hours at 575 to 650°F (302 to 343°C). The tensile strength of these hardened alloys ranges from 150,000 to 215,000 PSI.

Beryllium copper is usually supplied solution heat treated, aged, and cold worked. It can be machined in this condition with proper tooling. It is, however, sometimes necessary to anneal beryllium copper for further cold working.

Safety Note. Beryllium is a toxic metal and beryllium compounds are very toxic. Adequate protection should

able 2 Mechanical Properties of Some Heat-treatable Wrought Aluminum Alloys

lloy and Temper	Tensile Strength (ksi)		Elongation in 2 in Percent ½-in Dia Specimen	Brinell Hardness Number 10 mm Ball 500 kgf 30 Seconds	Shear Strength (ksi)	Modulus of Elasticity (ksi × 10³)	Fatigue Limit (ksi)
	Yield	Ultimate					
014-O	14	27	18	45	18	10.6	13
014-T3	41	64	—	—	—	10.6	—
014-T4	40	63	20	105	38	10.6	20
024-O	11	27	22	47	18	10.6	13
024-T3	50	70	—	120	41	10.6	13
024-T4	47	68	19	120	41	10.6	20
061-O	8	18	30	30	12	10.0	9
061-T4	21	35	25	95	30	10.0	14
063-O	7	13	—	25	10	10.0	8
063-T4	13	24	—	—	16	10.0	10
075-T6	73	83	11	150	48	10.4	22
178-T6	78	88	11	160	52	10.4	22

ore 1 Mechanical properties tables for wrought and cast aluminum and other nonferrous metals are available in manufacturers' reference materials.

ore 2. Ksi refers to thousands of pounds per square inch. Only four tempers of wrought aluminum were used for this table as they are particularly relevant

Casting process and metallurgy

Casting:

Molten metals are cast into molds and allowed to solidify for the purpose of producing the desired product by using different techniques(Processes).

Casting Processes:

1. Sand casting
2. Shell molding
3. Plaster mold casting
4. Ceramic-mold casting
5. Evaporated pattern casting (lost-foam process)
6. Investment casting (lost wax process)

Casting Processes (cont.):

7. Permanent mold casting
   - Pressure casting
   - Die casting
   - Vacuum casting
   - Slush casting
8. Centrifugal casting
9. Squeeze casting & semisolid metal forming
10. Composite mold casting operations

Sand casting process:

Introduction:

1. The traditional method of casting metals is in sand molds and has been used for a thousand-year period. Sand casting is still the most prevalent form of casting; in the United States alone, about 15 million tons of metal are cast by this method each year. Typical applications of sand casting include machine bases, large turbine impellers, propellers, plumbing fixtures, and numerous component for agricultural and railroad equipment.

2. **Types of Sands :** Most sand- casting operations use silica sand (SiO2) as mold material. Sand is not expensive and is suitable as mold material because of its high- temperature characteristics and high melting point. There are two general types of sand: naturally bonded (bank sand) and synthetic (lake sand). Because its composition can be controlled more accurately, synthetic sand is preferred by most foundries. For proper functioning, mold sand must be clean and preferably new.

3. **Sand Selection:** Several factors are important in the selection of sand for molds, and it involves certain tradeoffs with respect to properties. Sand having fine, round grains can be packed closely and, thus, forms a smooth mold surface. Although fine-grained sand enhances mold strength, the fine grains also lower mold permeability (penetrating through pores). Good permeability of molds and cores allows gases and steam evolved during the casting to escape easily. Resistance to high temperature and cost are also factors that are taken into consideration.

4. **Composition:** Sand 90% , clay 7%, and water 3%.

Sand molds

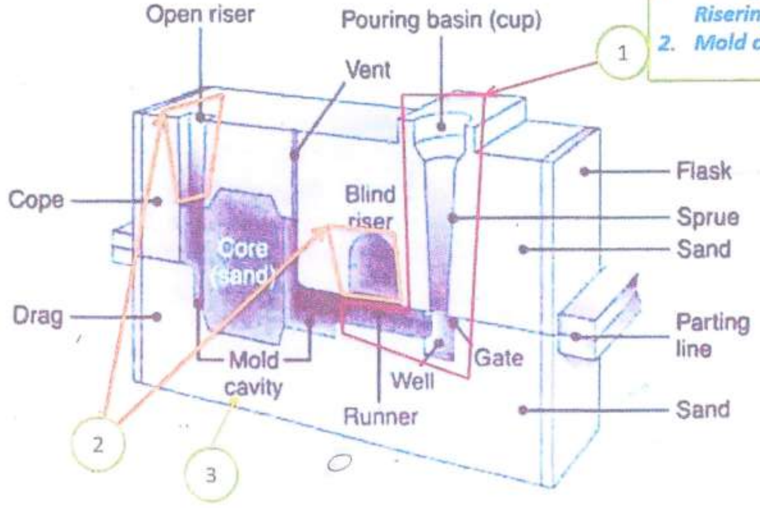
Sand molds are characterized by the types of sand that comprise them and by the methods used to produce them. There are three basic types of sand molds: green-sand, cold-box, and nobale molds. The most common mold material is green molding sand, which is a mixture of sand, clay, and water.

The term "green" refers to the fact that the sand in the mold is moist or damp while the metal is being poured into it. Green-sand molding is the least expensive method of making molds, and the sand is recycled easily for the subsequent use. In the skin-dried method, the mold surfaces are dried, either by storing the mold in air or by drying it with torches. Because of their higher strength, these molds generally are used for large castings.

Sand mold design:

The main parts of the mold:

1. *Gating and Risering systems*
2. *Mold cavity*

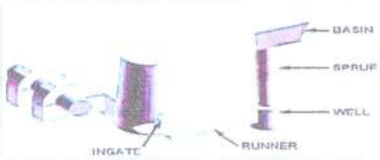


Schematic illustration of a sand mold, showing various features.

Gating system design

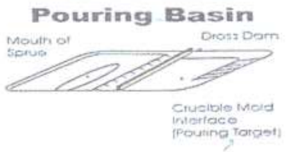
The elements of gating system are :

- *pouring basin, sprue and sprue base.*
- *runners , runner extension and ingates.*
- *Riser .*



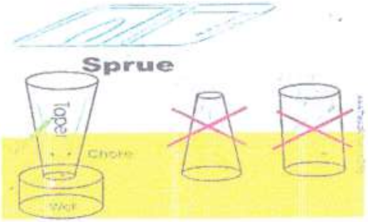
Pouring basin

The main function of a pouring basin is to reduce the momentum of the liquid flowing into the mold by settling first into it



Sprue and sprue base

It creates hydraulic pressure head, which will force the metal through the rest of the gating system and into the casting.



Design theoretical basic principles :

- **Bernoulli's theorem**
- **Law of mass continuity**
- **Pouring Time**
- **Reynold's Number**
- **Chvorinov's Rule**

Are used to calculate velocity in ideal fluid system

Chvorinov's Rule

- *relates the solidification time for a simple casting to the volume and surface area of the casting.*

$$t = B\left(\frac{V}{A}\right)^n$$

- *Where t is the solidification time, V is the volume of the casting, A is the surface area of the casting that contacts the mold, n is a constant, and B is the mold constant .*

Risering system design

is a part of gating system that forms the reservoir of molten metal necessary to compensate for losses due to shrinkage as the metal solidifies .

are only effective if three conditions are met:

1. The riser cools after the casting
2. The riser has enough material compensate for the casting shrinkage
3. The casting directionally solidifies towards the riser

The riser cools after the casting

In order for the riser to cool after the casting the riser must cool more slowly than the casting. ***Chvorinov's rule*** briefly states that the slowest cooling time is achieved with the greatest volume and the least surface area; geometrically speaking, this is a sphere. So, ideally, a riser should be a sphere, but this isn't a very practical shape to insert into a mold, so a cylinder is used instead. The height to diameter ratio of the cylinder varies depending on the material, location of the riser, size of the flask, etc.

In general we have two methods for finding riser's size :

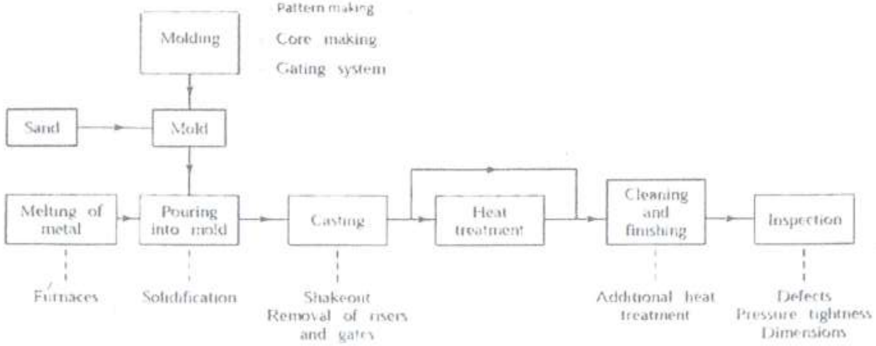
Method 1:

To calculate the minimum size of a riser is to use Chvorinov's rule by setting the solidification time for the riser to be longer than that of the casting. Any time can be chosen but 25% longer is usually a safe choice, which is written as follows:

$$t_{riser} = 1.25t_{casting}$$

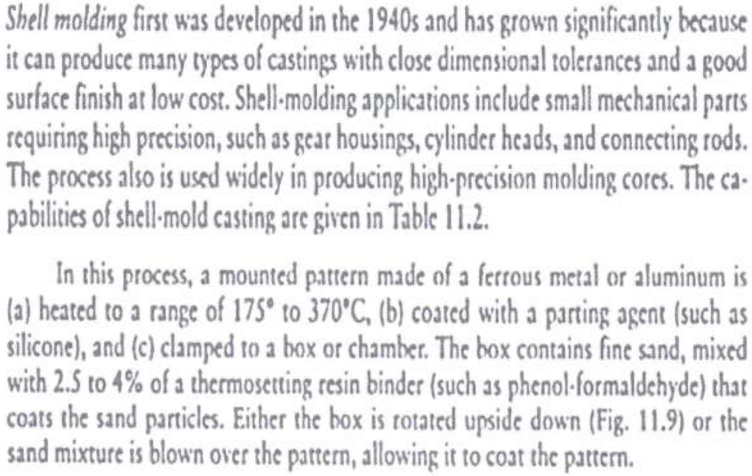
- Or $$\left(\frac{V}{A}\right)^n_{\text{riser}} = 1.25\left(\frac{V}{A}\right)^n_{\text{casting}}$$

Steps in Sand Casting



Outline of production steps in a typical sand-casting operation.

Shell molding



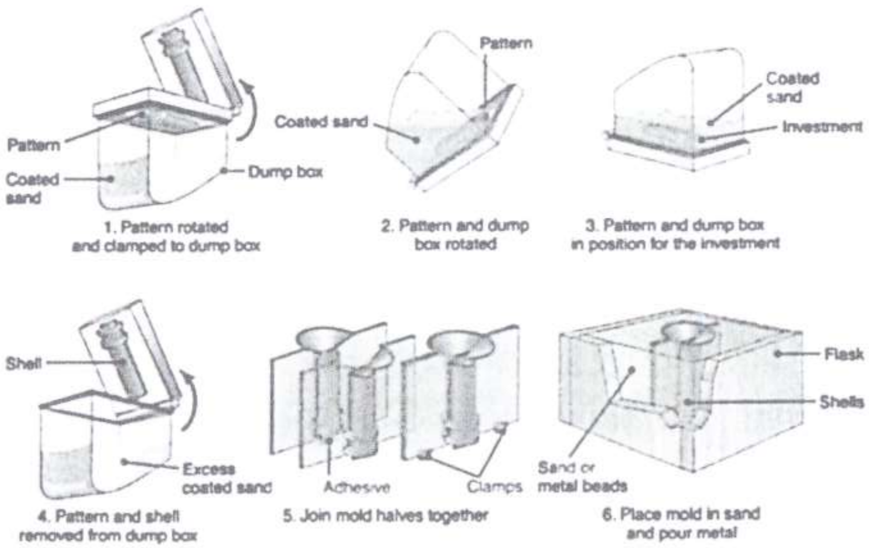
Shell molding first was developed in the 1940s and has grown significantly because it can produce many types of castings with close dimensional tolerances and a good surface finish at low cost. Shell-molding applications include small mechanical parts requiring high precision, such as gear housings, cylinder heads, and connecting rods. The process also is used widely in producing high-precision molding cores. The capabilities of shell-mold casting are given in Table 11.2.

In this process, a mounted pattern made of a ferrous metal or aluminum is (a) heated to a range of 175° to 370°C, (b) coated with a parting agent (such as silicone), and (c) clamped to a box or chamber. The box contains fine sand, mixed with 2.5 to 4% of a thermosetting resin binder (such as phenol-formaldehyde) that coats the sand particles. Either the box is rotated upside down (Fig. 11.9) or the sand mixture is blown over the pattern, allowing it to coat the pattern.

The assembly then is placed in an oven for a short period of time to complete the curing of the resin. In most shell-molding machines, the oven consists of a metal box with gas-fired burners that swing over the shell mold to cure it. The shell hardens around the pattern and is removed from the pattern using built-in ejector pins. Two half-shells are made in this manner and are bonded or clamped together to form a mold.

The thickness of the shell can be determined accurately by controlling the time that the pattern is in contact with the mold. In this way, the shell can be formed with the required strength and rigidity to hold the weight of the molten liquid. The shells are light and thin (usually 5 to 10 mm), and consequently, their thermal characteristics are different from those for thicker molds.

Shell sand has a much lower permeability than the sand used for green-sand molding, because a sand of much smaller grain size is used for shell molding. The decomposition of the shell-sand binder also produces a high volume of gas. Consequently, unless the molds are vented properly, trapped air and gas can cause serious problems in the shell molding of ferrous castings. The high quality of the finished casting can reduce cleaning, machining, and other finishing costs significantly. Complex shapes can be produced with less labor, and the process can be automated fairly easily.



1. Pattern rotated and clamped to dump box
2. Pattern and dump box rotated
3. Pattern and dump box in position for the investment
4. Pattern and shell removed from dump box
5. Join mold halves together
6. Place mold in sand and pour metal

FIGURE 11.9 The shell-molding process, also called the *dump-box* technique.

investment casting

Since the 1960s, investment-cast super-alloys have been replacing wrought counter-parts in high-performance gas turbines. Much development has been taking place in producing cleaner superalloys (nickel-based and cobalt-based). Improvements have been made in melting and casting techniques, such as vacuum-induction melting and using microprocessor controls. Impurity and inclusion levels have continually been reduced, improving the strength and ductility of these components. Such control is essential, because these parts operate at a temperature only about 50 C (90 F) below the solidus temperature of the alloy.

The microstructure of an integrally investment-cast, gas-turbine rotor is shown. Note the fine, uniform, equiaxed grains throughout the rotor cross-section. The procedures include the use of a nucleate addition to the molten metal, as well as close control of its superheat, pouring techniques, and control of cooling rate of the casting. In contrast, note the coarse- grain structure in the lower half of the figure showing the same type of rotor cast conventionally. This rotor has inferior properties compared with the fine-grained rotor. Due to developments in these processes, the proportion of cast parts to other parts in aircraft engines has increased from 20% to about 45% by weight.

investment casting

A variation of the investment-casting process is ceramic-shell casting. It uses the same type of wax or plastic pattern, which is dipped first in ethyl silicate gel and subsequently into a fluidized bed of fine-grained fused silica gel and subsequently into coarser-grained silica or zircon flour. The pattern then is dipped into coarser –grained silica to build up additional coatings and develop a proper thickness so that the pattern can withstand the thermal shock due to pouring. The rest of the procedure is similar to investment casting. This process is economical and is used extensively for the precision casting of steels and high-temperature alloys.

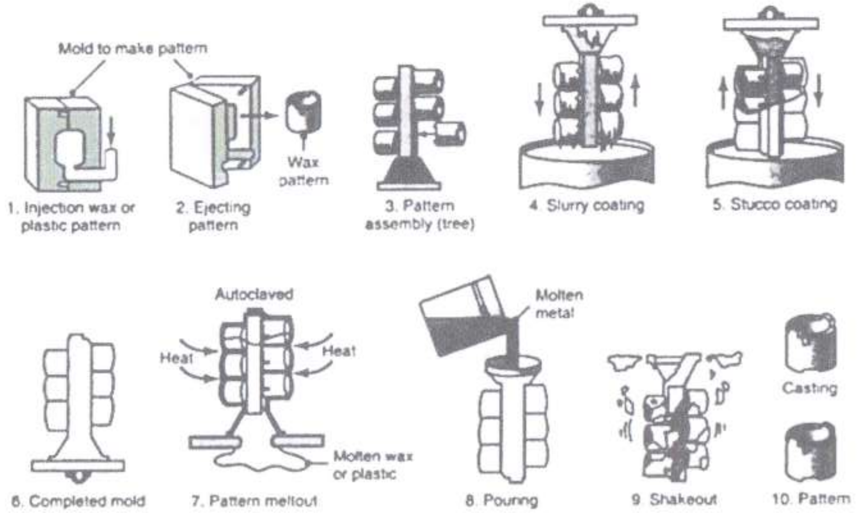


FIGURE 11.13 Schematic illustration of the investment casting (lost-wax) process. Castings produced by this method can be made with very fine detail and from a variety of metals. *Source:* Courtesy of Steel Founders' Society of America.

DIE- CASTING

The *die casting* process, developed in the early 1900s, is a further example of permanent-mold casting. Typical parts made by die casting are motor housings, engine blocks, business-machine and appliance components, hand tools, and toys. The weight of most castings ranges from less than 90 g to about 25 kg. Equipment costs, particularly the cost of dies, are somewhat high, but labor costs are generally low, because the process is now semi- or fully automated. Die casting is economical for large production runs. The capabilities of die casting are given in Table 11.2.

In this process, the molten metal is forced into the die cavity at pressures ranging from 0.7 to 700 MPa. The European term *pressure-die casting* (or simply die casting), which is described in this section, is not to be confused with the term *pressure casting* described in Section 11.3.4. There are two basic types of die-casting machines: hot-chamber and cold-chamber.

The hot-chamber process (Fig.) involves the use of a piston, which traps a certain volume of molten metal and forces it into the die cavity through a gooseneck and nozzle. Pressures range up to 35 MPa with an average of about 15 MPa. The metal is held under pressure until it solidifies in the die. To improve die life and to aid in rapid metal cooling (thereby reducing cycle time) dies usually are cooled by circulating water or oil through various passageways in the die block. Low-melting-point alloys (such as zinc, magnesium, tin, and lead) commonly are cast using this process. Cycle times usually range from 200 to 300 shots (individual injections) per hour for zinc, although very small components such as zipper teeth can be cast at rates of 18,000 shots per hour.

In the cold-chamber process (Fig.), molten metal is poured into the injection cylinder (*shot chamber*). The chamber is not heated, hence the term *cold chamber*. The metal is forced into the die cavity at pressures usually ranging from 20 to 70 MPa, although they may be as high as 150 MPa.

The machines may be horizontal (as in the figure) or vertical, in which case the shot chamber is vertical. High-melting-point alloys of aluminum, magnesium, and copper normally are cast using this method, although other metals (including ferrous metals) also can be cast. Molten-metal temperatures start at about 600°C for aluminum and some magnesium alloys, and increase considerably for copper-based and iron-based alloys.

Process capabilities and machine selection. Die casting has the capability for rapid production of strong, high-quality parts with complex shapes, especially with aluminum, brass, magnesium, and zinc (Table). It also produces good dimensional accuracy and surface details, so that parts require little or no subsequent machining or finishing operations (net-shape forming). Because of the high pressures involved, walls as thin as 0.38 mm are produced, which are thinner than those obtained by other casting methods. However, ejector marks remain, as may small amounts of flash (thin material squeezed out between the dies) at the die parting line.

TABLE

Properties and Typical Applications of Some Common Die-Casting Alloys

Alloy		Ultimate tensile strength (MPa)	Yield strength (MPa)	Elongation in 50 mm (%)	Applications
Aluminum 380 (3.5 Cu-8.5 Si)		320	160	2.5	Appliances, automotive components, electrical motor frames and housings
	13 (12 Si)	300	150	2.5	Complex shapes with thin walls, parts requiring strength at elevated temperatures
Brass 858 (60 Cu)		380	200	15	Plumbing fixtures, lock hardware, bushings ornamental castings
Magnesium AZ91 B (9 Al-0.7 Zn)		230	160	3	Power tools, automotive parts, sporting goods
Zinc	No. 3 (4 Al)	280	—	10	Automotive parts, office equipment, household utensils, building hardware, toys
	No. 5 (4 Al-1 Cu)	320	—	7	Appliances, automotive parts, building hardware, business equipment

Source: American Die Casting Institute.

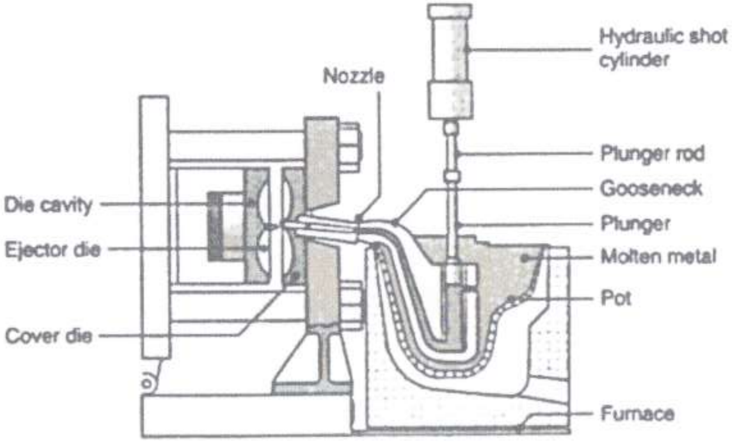
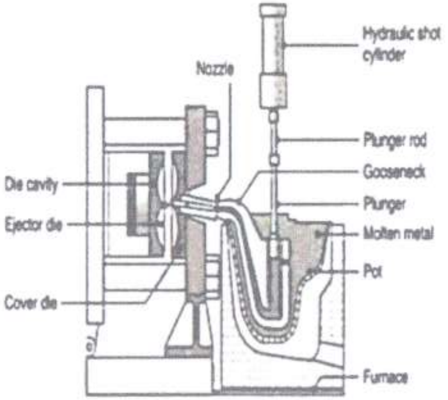
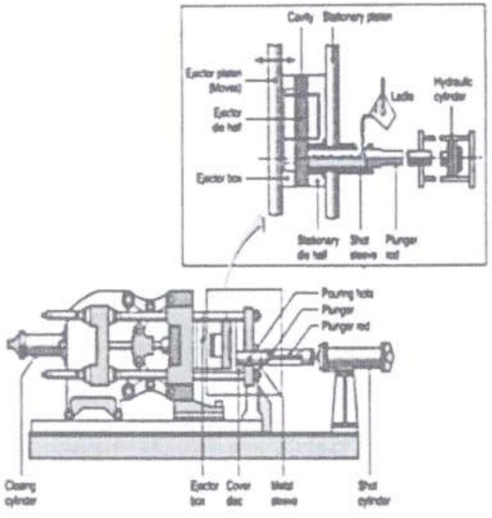


FIGURE 11.17 Schematic illustration of the hot-chamber die-casting process.



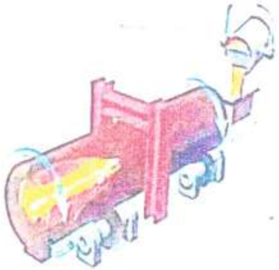
Schematic illustration of the hot-chamber die-casting process.



Schematic illustration of the cold-chamber die-casting process. These machines are large compared to the size of the casting, because high forces are required to keep the two halves of the dies closed under pressure.

Centrifugal casting

As its name implies, the *centrifugal-casting* process utilizes inertial forces (caused by rotation) to distribute the molten metal into the mold cavities—a method that was first suggested in the early 1800s. There are three types of centrifugal casting: true centrifugal casting, semicentrifugal casting, and centrifuging.



Centrifugal Casting:
Working Principle:
It works on basic principle of centrifugal force on a rotating Component. In this process, a mould is rotated about its central axis when the molten metal is poured into it. A centrifugal force acts on molten metal due to this rotation, which forces the metal at outer wall of mould. The mould rotates until the whole casting solidifies. The slag oxide and other inclusion being lighter, gets separated from metal and segregate towards the center.

Centrifugal Casting

True Centrifugal Casting

Application:-

C.I. water supply and sewerage pipes, steel [illegible] chemical [illegible] pressure [illegible] paper mill [illegible] etc

Semi Centrifugal Casting

Application:-

This process is used for making wheels, rings, rollers, sheaves, pulleys, flywheels, gear blanks, Turbo Supercharger diaphragm disk, steel railroad wheels, nozzles and similar parts etc

Centrifuging

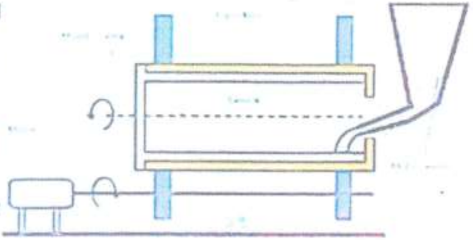
Application:

Products may be irregular or non symmetrical, valve bodies, plugs, valve bonnets, pillow blocks and yokes etc jewelery etc

---

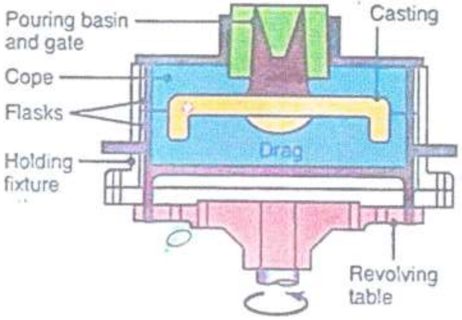
True Centrifugal Casting

- Molds may be made of cast iron or steel, copper, graphite, ceramic, or dry sand.
- Massive, thick metal molds with a thin refractory coating allow the molten metal to begin solidification faster and for the solidification to proceed from the wall of the mold toward the inside of the cast pipe.
- Another type of horizontal centrifugal casting uses a thick, highly insulating sand interface between the mold and the casting. When the metal introduced, the insulating nature of the sand prevents directional solidification, and hence the metal solidifies from the wall and from the inside pipe face at the same time.



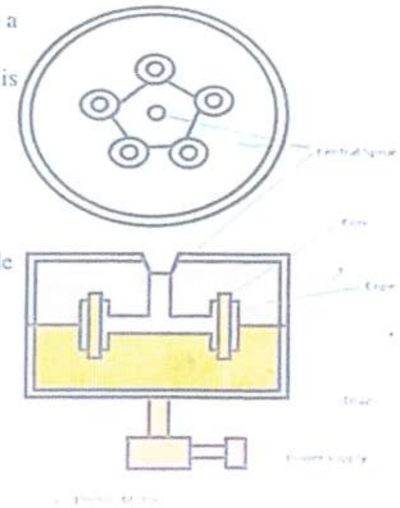
12.b. Semi-centrifugal casting

- Semi-centrifugal casting process is used to produce solid castings and hence, requires a core to produce hollow cavities.
- The process is used only for symmetrically shaped objects and the axis of rotation of the mould is *always vertical.*
- *Gear blanks, sheaves, wheels and pulley are the commonly produced parts by this process.*
- *Figure shows the process to produce a wheel shaped casting.*



3.Centrifuging

- When a group of small molds are arranged in a circle (to balance each other) around the central vertical axis of the flask and the flask is rotated about the vertical axis, the process is called centrifuge casting.
- It is clear that the molds are not symmetrical about the axis of rotation, that is , the axis of casting and the axis of rotation do not coincide with one another.
- Here again the centrifugal force is used to obtain higher pressure on the metal and get more dense castings. The molten metal will flow to all the molds under centrifugal force from a central feeding sprue.



Casting Metallurgy

Introduction

Types of castings

A. Ferrous casting alloys
B. Non ferrous casting alloys

A. Ferrous casting alloys:
0.0-0.02 % carbon -Ferrite
0.02-2.0% carbon -Steel
2.0-4.3 carbon -Cast iron

Cast iron contains 2.0-4.3 % carbon
Si = 2.3-3% added to increase fluidity

In this course, we will focus on ferrous alloys

Main Ferrous casting alloys

1. Gray cast iron
2. Ductile cast iron
3. White cast iron
4. Malleable
5. Compacted graphite iron (between flake graphite and nodular graphite cast iron)
6. Cast steels
7. Cast stainless steel

Gray cast iron

***Ma*in properties:**

- Gray color
- Hard
- Weak in tension
- Graphite exists in the form of flakes
- Microstructure: graphite flakes, pearlite, and ferrite

Microstructure: graphite flakes, pearlite, and ferrite

Ductile cast iron

- Ductile cast iron is known by ***several names***: nodular iron, ductile iron, and spheroidal graphite iron. It gets the names from the ball-like form of the graphite in the metal and the very ductile property it exhibits. Nodular cast iron combines many of the advantages of cast iron and steel. ***Its advantages include*** good castability, toughness, machinability, good shock and wear resistance, weld-ability, low melting point, corrosion resistance, and hardenability.

- ***The formation of the graphite into a ball*** form is accomplished by adding certain elements such as magnesium and cerium to the melt just prior to casting. The vigorous mixing reaction caused by adding these elements results in a homogenous spheroidal or ball-like structure of the graphite in the cast iron. The iron matrix or background material can be heat treated to form any one of the microstructures associated with steels, such as ferrite, bainite (as in austempered ductile iron), pearlite, or martensite

---

White cast iron

- White cast iron is very hard, brittle, and virtually non machinable. In some cases it is used where there is a need for resistance to abrasion. White cast iron is often found in combination with other cast iron, such as gray cast iron, to improve the hardness and wear-resistant properties.

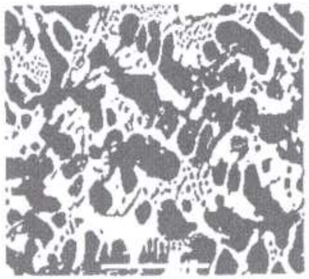
- There are basically ***two ways of obtaining white cast iron***

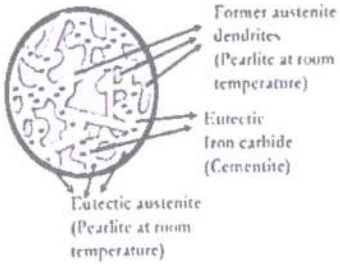
1. by lowering the iron's silicon content;
2. by rapid cooling, which in this case yields what is called chilled cast iron. When cooled at a rapid rate, the excess carbon forms iron carbide and not graphite, thus making white cast iron.

White cast iron

Many times it is advantageous to have a hard, wear-resistant surface on the part, such as a bearing surface or outer rim. This is easily accomplished by putting chill plates in the mold so that the molten iron will cool faster in these localized areas, creating white cast iron.

The microstructure of white cast iron





Malleable cast iron

Malleable cast iron is noted for its strength, toughness, ductility, castability, and machinability. In the process of making malleable cast iron, it is first necessary to begin with white cast iron.

The white cast iron is then heat treated as follows:

1. Heat to about 1700°F (927°C).
2. Hold at this temperature for about 15 hours. This breaks down the iron carbide to austenite and graphite.
3. Slow cool to about 1300°F (704°C).
4. Hold at this temperature for approximately 15 hours.
5. Air cool to room temperature.

This process breaks down the iron carbide into additional austenite and graphite. Upon cooling, the graphite will form into clusters or balls. The austenite will take on any one of the transformation products, depending on the cooling rate

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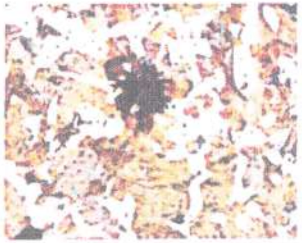
Malleable iron starts as a white iron casting that is then heat treated for a day or two at about 950 °C (1,740 °F) and then cooled over a day or two. As a result, the carbon in iron carbide transforms into graphite and ferrite plus carbon (austenite). The slow process allows the surface tension to form the graphite into spheroidal particles rather than flakes. Due to their lower aspect ratio, the spheroids are relatively short and far from one another, and have a lower cross section vis-a-vis a propagating crack or phonon. They also have blunt boundaries, as opposed to flakes, which alleviates the stress concentration problems found in grey cast iron. In general, the properties of malleable cast iron are more like those of mild steel. There is a limit to how large a part can be cast in malleable iron, as it is made from white cast iron.

Uses include electrical fittings, hand tools, pipe fittings, washers, brackets, fence fittings, power line hardware, farm equipment, mining hardware, and machine parts

Malleable iron is cast as white iron. The structure of Malleable cast iron is a metastable carbide in a pearlitic matrix. Through an annealing heat treatment, the brittle structure as first cast is transformed into the malleable form. Carbon agglomerates into small roughly spherical aggregates of graphite leaving a matrix of ferrite or pearlite according to the exact heat treatment used.

Three basic types of malleable iron are recognized within the casting industry: *blackheart* malleable iron, *whiteheart* malleable iron and *pearlitic* malleable

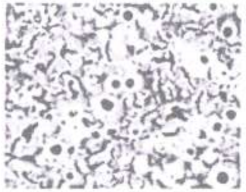


Compacted graphite iron

Compacted graphite iron (CGI), also known as **vermicular graphite iron** especially in non-English speaking countries,is a metal which is gaining popularity in applications that require either greater strength, or lower weight than cast iron.

R.D. Schelleng obtained a patent for the production of compacted graphite iron in 1965

The graphite in compacted graphite iron differs in structure from that in gray iron because the graphite particles are shorter and thicker



The first commercial application for compacted graphite iron was for the brake discs for high-speed rail trains. More recently compacted graphite iron has been used for diesel engine blocks. It has proven to be useful in the manufacture of V topology diesel engines where the loading on the block is very high between the cylinder banks, and for heavy goods vehicles which use diesel engines with high combustion pressures.

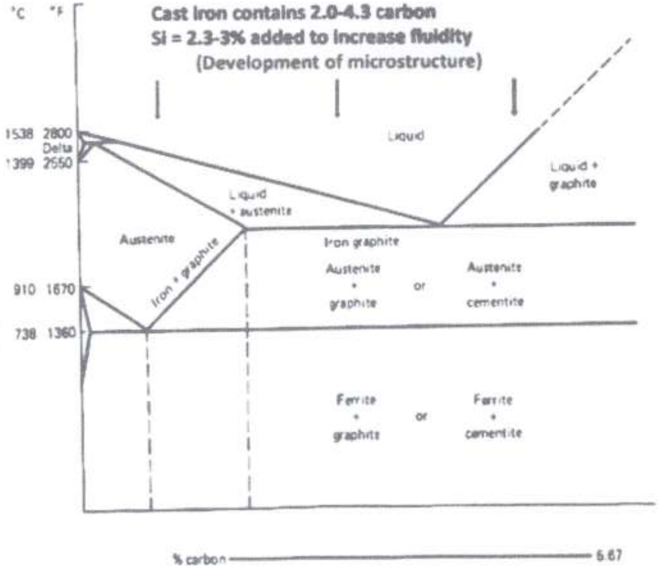
It is also used for turbo housings and exhaust manifolds, in the latter case to reduce corrosion.

Non ferrous casting alloys

1. **Al-base alloys**
2. **Mg-base alloys**
3. **Cu-base alloys**
4. **Zn-base alloys**
5. **High temperature base alloys such as Ti.....etc.**

Phase Diagram

Casting: Molten metals are cast into molds and allowed to solidify for the purpose of producing the desired product by using different techniques(Processes)


Cast iron contains 2.0-4.3 carbon
Si = 2.3-3% added to increase fluidity
(Development of microstructure)

Iron-graphite equilibrium diagram.

The Development of the Microstructure

Casting: Molten metals are cast into molds and allowed to solidify for the purpose of producing the desired product by using different techniques(Processes)

1. *When a pure metal solidifies, each crystal begins to form independently from a nucleus or 'centre of crystallisation'.*
2. *The nucleus will be a simple unit of the appropriate crystal lattice, and from this the crystal will grow.*
3. *The crystal develops by the addition of atoms according to the lattice pattern it will follow, and rapidly begins to assume visible proportions in what is called a 'dendrite' (Gk 'dendron', a tree). This is a sort of crystal skeleton, rather like a backbone from which the arms begin to grow in other directions, depending upon the lattice pattern. From these secondary arms, tertiary arms begin to sprout, somewhat similar to the branches and twigs of a fir-tree. In the metallic dendrite, however, these branches and twigs conform to a rigid geometrical pattern. A metallic crystal grows in this way because heat is dissipated more quickly from a point, so that it will be there that the temperature falls most quickly leading to the formation of a rather elongated skeleton (Fig. 3.10).*

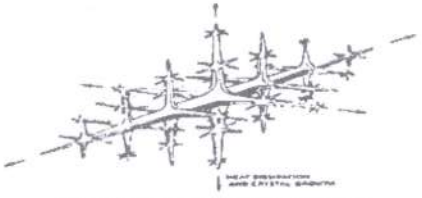


Fig. 3.10 The early stages in the growth of a metallic dendrite

Plate 3.1 Dendritic growth
[illegible]

- *Several locations will show the same behavior*
- *Dendrite grows and thickens and the outer arms begin to contact with neighbouring dendrites*
- *Lattices will meet at different angles*
- *Once solidification complete:*
- *If the metal we have been considering is pure we shall see no evidence whatever of dendritic growth, since all atoms are identical.*
- *Dissolved impurities, however, will often tend to remain in the molten portion of the metal as long as possible, so that they are present in that part of the metal which ultimately solidifies in the spaces between the dendrite arms. Since their presence will often cause a slight alteration in the colour of the parent metal, the dendritic structure will be revealed on microscopical examination. The areas containing impurity will appear as patches between the dendrite arms (Fig. below)*

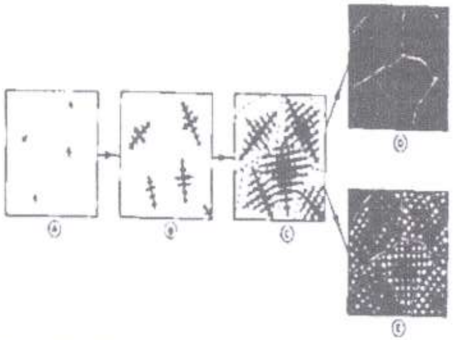


Fig. 3.11 The dendritic growth of metallic crystals from the liquid state
A solid pure metal (D) gives no hint of its dendritic origin since all atoms are identical, but an impure metal (E) carries the impurities between the dendritic arms, thus revealing the initial skeleton.

Annealing of castings

- *The most suitable treatment for a large casting involves heating it slowly up to a temperature about 40°C above its upper critical (thus the annealing temperature depends upon the carbon content of the steel), holding it at that temperature only just long enough for a uniform temperature to be attained throughout the casting and then allowing it to cool slowly in the furnace. This treatment not only introduces the improvements in mechanical properties associated with fine grain but also removes mechanical strains set up during solidification.*
- *As the lower critical temperature (723°C) is reached on heating, the patches of pearlite transform to austenite but these new crystals of austenite are very small since each patch of pearlite gives rise to many new austenite crystals. It is upon this fact that the complete success of this type of annealing process depends. As the temperature rises, the Widmanstatten-type plates of ferrite are dissolved by the austenite until, when the upper critical temperature is reached, the structure consists entirely of finegrained austenite. Cooling causes reprecipitation of the ferrite, but, since the new austenite crystals are small, the precipitated ferrite will also be distributed as small particles. Finally, as the lower critical temperature is reached, the remaining small patches of austenite will transform to pearlite. The structural changes taking place during annealing are illustrated dia-grammatically in Fig. 11.9.*

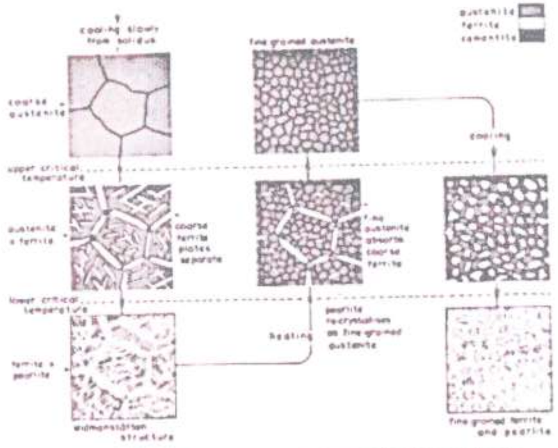


Fig. 11.9 Structural changes occurring during the annealing of a steel casting (approx. 0.35% carbon). The as-cast Widmanstatten structure is reheated to some temperature above its upper critical and then allowed to cool in the furnace.

Normalizing of castings

Normalising resembles the 'full' annealing of castings in that the maximum temperature attained is similar. It is in the method of cooling that the processes differ. Whilst, in annealing, cooling is retarded, in normalising the steel is removed from the furnace and allowed to cool in still air. This relatively rapid method of cooling limits grain growth in normalising, whilst the ferrite/cementite lamellae in pearl-ite will also be much finer. For both reasons the mechanical properties are somewhat better than in an annealed component. Moreover, the surface finish of a normalised article is often superior to that of an annealed one when machined, since the high ductility of the latter often gives rise to local tearing of the surface.

The type of structure obtained by normalising will depend largely upon the thickness of cross-section. Thin sections will give a much finer grain than thick sections, the latter differing little in structure from an annealed section.

Defects in castings

1. Blow-holes and porosity
2. Shrinkage
3. Segregation of impurities (the presence of low melting segregates along grain boundaries increase the tendency for hot tearing)
4. Incomplete casting
5. Line and point defects

Porosity and Blow-holes

Porosity

If the metal is cooled too rapidly during solidification, molten metal is often unable to 'feed' effectively into the spaces which form between the dendrites due to the shrinkage which accompanies freezing. These spaces then remain as cavities following the outline of the solid dendrite. Such shrinkage cavities can usually be distinguished from blow-holes formed by dissolved gas.

The former are of distinctive shape and occur at the crystal boundaries, whilst the latter are quite often irregular in form and occur at any point in the crystal structure (Fig. 3.12).

Blow –holes

These are caused by:

1. **furnace gases** which have dissolved in the metal during melting:

Gas which has dissolved freely in the molten metal will be much less soluble in the solid metal. Therefore, as the metal solidifies, gas will be forced out of solution. Since dendrites have already formed, the bubbles of expelled gas become trapped by the dendrite arms and are prevented from rising to the surface. Most aluminium alloys and some of the copper alloys are susceptible to 'gassing' of this type, caused mainly by hydrogen dissolved from the furnace atmosphere. The difficulty can be overcome only by making sure that there is no dissolved gas in the melt prior to casting

2. by chemical reactions which have taken place in the melt.

Any iron oxide (present as oxygen ions) in the molten steel will tend to be reduced by carbon according to the following equation:

$$FeO + C = Fe + CO$$

This is what is commonly called a reversible reaction and the direction in which the resultant reaction proceeds depends largely upon the relative concentrations of the reactants and also upon the temperature. When carbon (in the form of anthracite for example) is added to the molten steel the reaction proceeds strongly to the right and since carbon monoxide, a gas, is lost to the system the reaction continues until very little FeO remains in equilibrium with the relatively large amount of carbon present. As the ingot begins to solidify, it is almost pure iron of which the initial dendrites are composed. This causes an increase in the concentration of carbon and the oxide, FeO, in the remaining molten metal, thus upsetting chemical equilibrium so that the above reaction will commence again. The bubbles of carbon monoxide formed are trapped by the growing dendrites, producing blow-holes. The formation of blow-holes of this type is prevented by adequate 'killing' of the steel before it is cast—that is, by adding a sufficiency of a deoxidising agent such as ferromanganese. This removes residual FeO and prevents the FeO-C reaction from occurring during subsequent solidification. In some cases the FeO-C reaction is utilised as in the production of 'rimmed' ingots

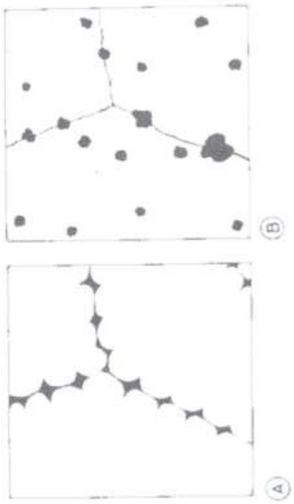


Fig. 3.12 Porosity in cast metals
Shrinkage cavities (A) tend to follow the shape of the dendritic arms and occur at the crystal boundaries whilst gas porosity (B) is usually of irregular shape and occurs at almost any point in the structure

Plate 3.28 Shrinkage cavities (black areas) in cast tin bronze
These roughly follow the shape of the original dendrites and occur in that part of the alloy to solidify last × 200 Etched in ammonia-hydrogen peroxide

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Shrinkage

The crystalline structure of most metals of engineering importance represent a close packing of atoms. Consequently solid metals occupy less space than they do as liquids and shrinkage takes place during solidification as a result of this decrease in volume. If the mould is of a design such that isolated pockets of liquid remain when the outside surface of the casting is solid, shrinkage cavities will form. Hence the mould must be so designed that there is always a 'head' of molten metal which solidifies last and can therefore 'feed' into the main body of the casting as it solidifies and shrinks. Shrinkage is also responsible for the effect known as 'piping' in cast ingots. Consider the ingot mould (Fig. 3.14A) filled instantaneously with molten steel. That metal which is adjacent to the mould surface solidifies almost immediately, and as it does so it shrinks. This causes the level of the remaining metal to fall slightly, and as further solidification takes place the process is repeated, the level of the remaining liquid falling still further. This sequence of events continues to be repeated until the metal is completely solid and a conical cavity or 'pipe' remains in the top portion of the ingot. With an ingot shaped as shown it is likely that a secondary pipe would be formed due to the shrinkage of trapped molten metal when it solidifies. It is usually necessary to shape large ingots in the way shown in Fig. 3.14A, that is, small end upwards, so that the mould can be lifted from the solidified ingot. Therefore various methods of minimising the pipe must be used (2.21—Part II). One of the most important of these methods is to pour the metal into the mould so that solidification almost keeps pace with pouring. In this way molten metal feeds into the pipe formed by the solidification and consequent shrinkage of the metal. Smaller ingots can be cast into moulds which taper in the opposite direction to that shown in Fig. 3.14A, ie large end upwards (Fig. 3.14B), since these can be trunnion-mounted to make ejection of the ingot possible.

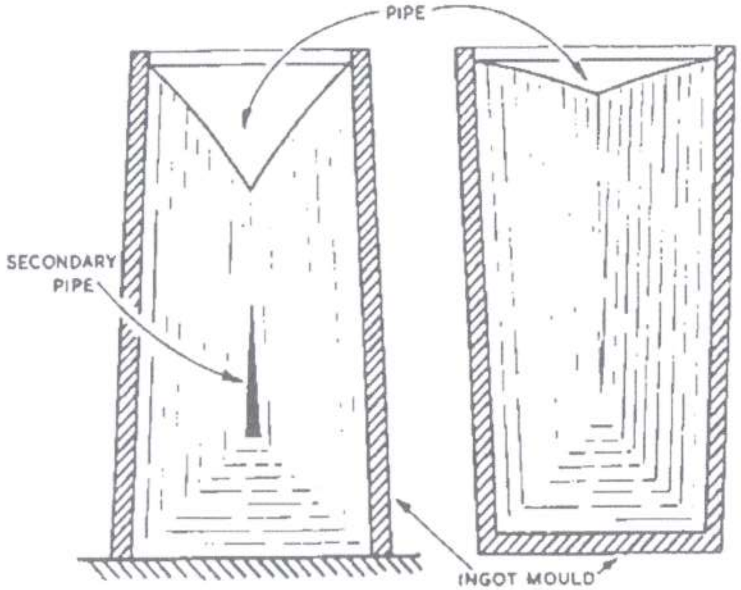


Fig. 3.14 The influence of the shape of the mould on the extent of piping in a steel ingot

Casting Design Modifications

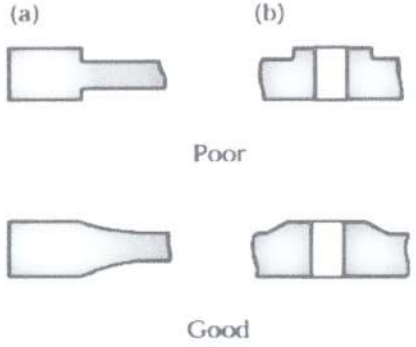


Figure 12.1 Suggested design modifications to avoid defects in castings. Note that sharp corners are avoided to reduce stress concentrations.

Casting Cross-Sections

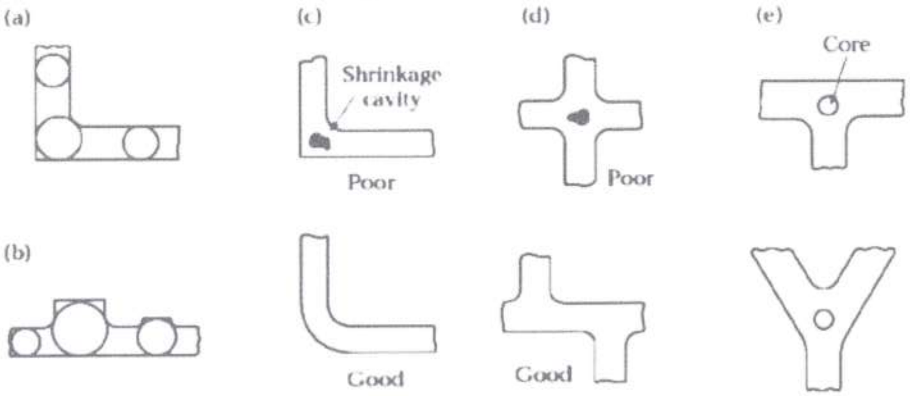
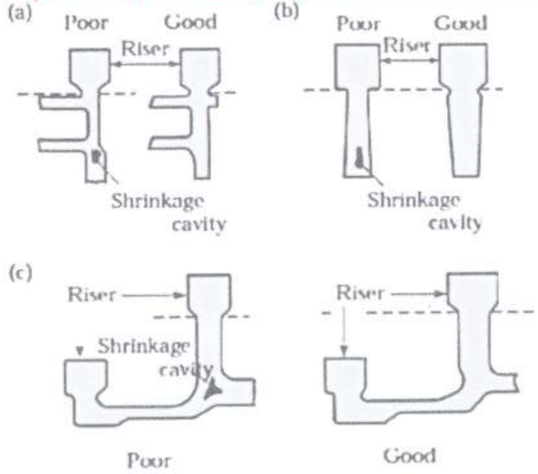


Figure 12.2 Examples of designs showing the importance of maintaining uniform cross- sections in castings to avoid hot spots and shrinkage cavities.

Avoiding Shrinkage Cavities

Figure 12.3 Examples of design modifications to avoid shrinkage cavities in castings. Source: *Steel Castings Handbook*, 5th ed. Steel Founders' Society of America, 1980. Used with permission.



Segregation of impurities

- *There is a tendency for dissolved impurities to remain in that portion of the metal which solidifies last. The actual mechanism of this type of solidification will be dealt with later (8.23), and it will be sufficient here to consider its results.*
- *The dendrites which form first are of almost pure metal, and this will mean that the impurities become progressively more concentrated in the liquid which remains. Hence the metal which freezes last at the crystal boundaries contains the bulk of the impurities which were dissolved in the original molten metal. This local effect is known as minor segregation (Fig. 3.15A).*
- *As the columnar crystals begin to grow inwards, they will push in front of them some of the impurities which were dissolved in the molten metal from which they themselves solidified. In this way there is a tendency for much of the impurities in the original melt to become concentrated in the central pipe. If a vertical section of an ingot is polished and etched, these impurities show as V-shaped markings in the area of the pipe (Fig. 3.15B). The effect is called major segregation.*
- *With very large ingots the temperature gradient may become very slight towards the end of the solidification process, and it is common for the band of metal which has become highly charged with impurities, just in front of the advancing columnar crystals, to solidify last. Some impurities, when dissolved in a metal, will depress its freezing point considerably (similarly when lead is added to tin a low melting point solder is produced).*

Segregation of impurities (cont.)

- *Hence the thin band of impure metal just in advance of the growing columnar crystals has a much lower freezing point than the relatively pure molten metal at the centre. Since the temperature gradient is slight, this metal at the centre may begin to solidify in the form of equi-axed crystals, so that the impure molten metal is trapped in an intermediate position. This impure metal therefore solidifies last, causing inverted V-shaped markings to appear in the etched section of such an ingot. It is known as 'inverse-vee' segregation (Fig. 3.15C). Rimming steels contain no heavily-segregated areas because of the mechanical stirring action introduced by the evolution of carbon monoxide during the FeO/C reaction (3.21). Of these three types of segregation, minor segregation is probably the most deleterious in its effect, since it will cause overall brittleness of the castings and, depending upon the nature of the impurity, make an ingot hot- or cold-short, that is, liable to crumble during hot- or cold-working processes.*
- *From the foregoing remarks it will be evident that a casting, suffering as it may from so many different types of defect, is one of the more variable and least predictable of metallurgical structures. In some cases we can detect the presence of blow-holes and other cavities by the use of X-rays, but other defects may manifest themselves only during subsequent service. Such difficulties are largely overcome when we apply some mechanical working process during which such defects, if serious, will become apparent by the splitting or crumbling of the material undergoing treatment. At the same time a mechanical working process will give a product of greater uniformity in so far as structure and mechanical properties are concerned. Thus, all other things being equal, a forging is likely to be more reliable in service than a casting. Sometimes, however, such factors as intricate shape and cost of production dictate the choice of a casting. We must then ensure that it is of the best possible quality*

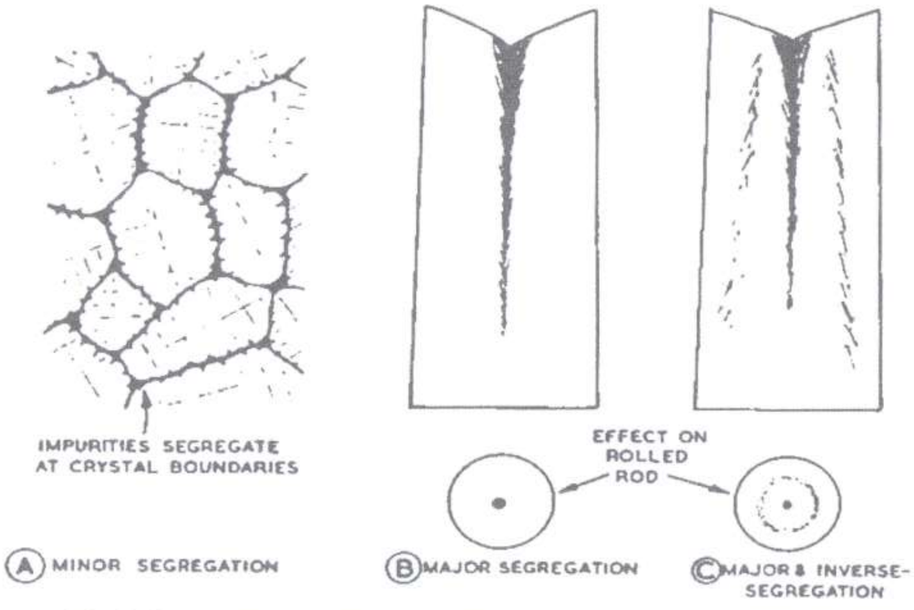


Fig. 3.15 Types of segregation which may be encountered in steel ingots.

Line and point defects

In the foregoing sections we have been dealing with such defects as are likely to occur in cast metals. These defects may be so large that a microscope is not necessary to examine them. Others are small yet still within the range of a simple optical microscope. On the atomic scale however metallic structures which would be regarded as being of very high quality in the industrial sense nevertheless consist of crystals which contain numerous 'line' and 'points' defects scattered throughout the crystal lattice. These defects (Fig. 3.16) occur in wrought as well as in cast metals and though small in dimensions have considerable influence on mechanical properties.

Joining processes

Observations:

1. ***Products made of one component such as paper clips, nails, steel ball***
2. ***Products made of two components such as kitchen knives, cooking spots, ...etc.***
3. ***Products made of more than two components such as computers, cars, ...etc***

Reasons behind assembly operations:

1. *Product may be impossible to manufacture as a single piece*
2. *More economic to manufacture the product as individual parts*
3. *Different properties may be desirable (automotive brake shoes-surface and bulk)*
4. *For maintenance purposes*
5. *For transportation purposes*

Joining processes fall into three major categories:

1. ***Welding***
2. ***Adhesive bonding***
3. ***Mechanical fastening***

Our focus is welding

Welding processes fall into the following three categories:

1. *Fusion welding* - coalescence is accomplished by melting the two parts to be joined, in some cases adding filler metal to the joint. *Examples: arc welding, resistance spot welding, oxyfuel gas welding*
2. *Solid state welding* - heat and/or pressure are used to achieve coalescence, but no melting of base metals occurs and no filler metal is added. *Examples: forge welding, diffusion welding, friction welding*
3. ***Brazing and soldering (uses fillers)***

Examples of WELDING PROCESSES

Arc Welding (AW)

A fusion welding process in which coalescence of the metals is achieved by the heat from an electric arc between an electrode and the work

- ***Electric energy from the arc produces temperatures ~ 10,000 F (5500 C), hot enough to melt any metal***
- ***Most AW processes add filler metal to increase volume and strength of weld joint***

Arc Welding

A pool of molten metal is formed near electrode tip, and as electrode is moved along joint, molten weld pool solidifies in its wake

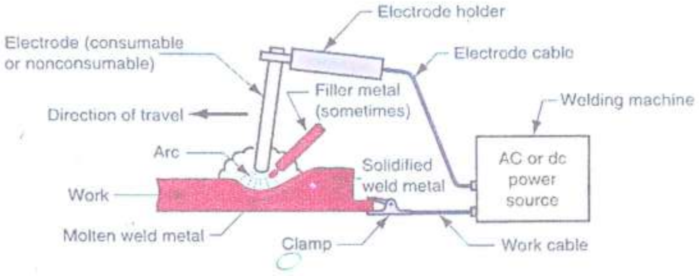


Figure 31.1 Basic configuration of an arc welding process.

What is an Electric Arc?

An electric arc is a discharge of electric current across a gap in a circuit

- *It is sustained by an ionized column of gas (plasma) through which the current flows*
- *To initiate the arc in AW, electrode is brought into contact with work and then quickly separated from it by a short distance*

Two Basic Types of AW Electrodes

- *Consumable – consumed during welding process*
  - *–Source of filler metal in arc welding*
- *Nonconsumable – not consumed during welding process*
  - *–Filler metal must be added separately*

Consumable Electrodes

Forms of consumable electrodes

Welding rods (a.k.a. sticks) are 9 to 18 inches and 3/8 inch or less in diameter and must be changed frequently

Weld wire can be continuously fed from spools with long lengths of wire, avoiding frequent interruptions

In both rod and wire forms, electrode is consumed by arc and added to weld joint as filler metal

Nonconsumable Electrodes

- *Made of tungsten which resists melting*
- *Gradually depleted during welding (vaporization is principal mechanism)*
- *Any filler metal must be supplied by a separate wire fed into weld pool*

Arc Shielding

At high temperatures in AW, metals are chemically reactive to oxygen, nitrogen, and hydrogen in air

**Mechanical properties of joint can be seriously degraded by these reactions*

**To protect operation, arc must be shielded from surrounding air in AW processes*

Arc shielding is accomplished by:

****Shielding gases, e.g., argon, helium, CO_2***

****Flux***

Various Flux Application Methods

- *Pouring granular flux onto welding operation*
- *Stick electrode coated with flux material that melts during welding to cover operation*
- *Tubular electrodes in which flux is contained in the core and released as electrode is consumed*

Power Source in Arc Welding

- *Direct current (DC) vs. Alternating current (AC)*
  - *–AC machines less expensive to purchase and operate, but generally restricted to ferrous metals*
  - *–DC equipment can be used on all metals and is generally noted for better arc control*

Other Fusion Welding Processes

FW processes that cannot be classified as arc, resistance, or oxyfuel welding use unique technologies to develop heat for melting

Applications are typically unique Processes which include:

Electron beam welding

Laser beam welding

Electroslag welding

Thermit welding

Solid State Welding (SSW)

Coalescence of part surfaces is achieved by:

**Pressure alone, or Heat and pressure*

**If both heat and pressure are used, heat is not enough to melt work surfaces*

**For some SSW processes, time is also a factor*

**No filler metal is added*

**Each SSW process has its own way of creating a bond at the faying surfaces*

Solid State Welding Processes

- *Forge welding*
- *Cold welding*
- *Roll welding*
- *Hot pressure welding*
- *Diffusion welding*
- *Explosion welding*
- *Friction welding*
- *Ultrasonic welding*

Weldability:

It is the Capacity to be welded into a specific structure that has certain properties and characteristics and will satisfactorily meet service requirements. Thorough knowledge of the phase diagram is essential

Factors affect weldability are:

1. *composition (carbon content, alloying elements, microstructure)*
2. *Properties such as strength, toughness, ductility, notch sensitivity, elastic modulus, specific heat, melting point, thermal expansion, surface tension characteristics of the molten metal, corrosion resistance.*
3. *Preparation of surface affects the nature of oxide-films and adsorbed gases*
4. *Shielding gases, fluxes, moisture, coating on electrodes, welding speed, cooling rate*
5. *Ost welding techniques such as stress relieving and heat treating.*