HEAT TREATMENT PROCESSES

- **ANNEALING, NORMALISING AND HARDENING, HARDENABILITY**

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HEAT TREATMENT

Heat treatment is a group of industrial, thermal and metalworking processes used to alter the physical, and sometimes chemical, properties of a material. The most common application is metallurgical. Heat treatments are also used in the manufacture of many other materials, such as glass. Heat treatment involves the use of heating or chilling, normally to extreme temperatures, to achieve the desired result such as hardening or softening of a material. Heat treatment techniques include annealing, case hardening, precipitation strengthening, tempering, carburizing, normalizing and quenching. Although the term heat treatment applies only to processes where the heating and cooling are done for the specific purpose of altering properties intentionally, heating and cooling often occur incidentally during other manufacturing processes such as hot forming or welding.

Different types of Heat Treatment

- Annealing
- Normalizing and Hardening
- Hardenability

Annealing

Annealing is a heat treatment process that changes the physical and sometimes also the chemical properties of a material to increase ductility and reduce the hardness to make it more workable.

The annealing process requires the material above its recrystallization temperature for a set amount of time before cooling. The cooling rate depends upon the types of metals being annealed. For example, ferrous metals such as steel are usually left to cool down to room temperature in still air while copper, silver and brass can either be slowly cooled in air or quickly quenched in water.

The heating process cause atoms to migrate in the crystal lattice and the number of dislocations reduces, which leads to the change in ductility and hardness. The heat-treated material recrystallizes as it cools. The crystal grain size and phase composition depend on the heating and cooling rates and these, in turn, determine the material properties.

Hot or cold working of the pieces of metal following annealing alters the material structure once more, so further heat treatments may be required to attain the desired properties.

However, with knowledge of material composition and phase diagram, heat treating can soften metals and prepare them for further working such as forming, shaping and stamping, as well as preventing brittle failure.

Who Discovered Annealing?

Annealing dates back hundreds of years, as evidenced by the word itself, which comes from the Middle English ‘anelen,’ meaning to set on fire or kindle, as well as bake and temper.

Middle English was spoken and written in England from 1150 until 1500 and is a descendant of Old English. The term had spelling variations, such as the Middle English ‘onǣlan,’ and was used as in this instruction from 1400, ‘Take þe plates of bras pannes or of cawdrouns and anele hem in þe fire rede hoot’ (“Take the plates of brass pans or of cauldrons and anneal them in the fire red hot”).

While we do not know exactly who discovered annealing, the etymology shows that it was in practice at least 900 years ago.

How does an Annealing Furnace Work?

An annealing furnace works by heating a material above the recrystallization temperature and then cooling the material once it has been held at the desired temperature for a suitable length of time. The material recrystallizes as it cools once the heating process has caused atom movement to redistribute and eradicate dislocations in the workpiece.

Annealing works in **three stages** – the recovery stage, recrystallization stage and the grain growth stage. These work as follows:

1. Recovery Stage

This stage is where the furnace or other heating device is used to raise the temperature of the material to such a point that the internal stresses are relieved.

2. Recrystallization Stage

Heating the material above its recrystallization temperature but below its melting point causes new grains to form without any residual stresses.

3. Grain Growth Stage

Cooling the material at a specific rate causes new grains to develop. After which the material will be more workable. Subsequent operations to alter mechanical properties can be carried out following annealing.

Types of annealing:

1. Complete Annealing:
In this process, steel is heated to 30 to 50 degrees Celsius above the critical temperature of steel and this temperature is maintained for specified period of time, heat preservation for a period of time after slow cooling .
The cooling rate may be about 10 degree C per hour.
After that, material is allowed to cool down slowly inside the furnace without any forced cooling.
Complete annealing is used in worked sheets, forging and casting made from medium and high carbon steels.
Low carbon steel has low hardness and is not applicable to machining.

After complete annealing process, Fe3C2 precipitated in mesh along the grain boundary, the strength, hardness, plasticity and toughness of steel are significantly reduced.

Purpose of Complete Annealing:

Complete annealing is done to get all the changes in the properties of the metals like

1. Producing equilibrium microstructure.
2. Increase in ductility
3. Reduction in hardness, strength, brittleness and
4. Removal of internal stresses.

The microstructure after annealing contains coarse ferrite and pearlite.

2. Process Annealing:

This process is mainly suited for low carbon steel. In this process material is heated up to a temperature just below the lower critical temperature of steel or above its recrystallisation temperature and then is allowed to cool slowly for some time.

Cold worked steel normally have increased hardness and decrease ductility making it difficult to work. Process annealing improves these characteristics by making it more ductile and decreasing its hardness. This is mainly carried out on cold rolled steel like wire drawn steel, etc.

Purpose of Process Annealing:

1. Process annealing is done for recrystallization of metal.
2. During process annealing, new equiaxed, strain-free grains nucleate at high-stress regions in the cold-worked microstructure, and hence hardness

and strength decrease whereas ductility increases.
3. The main aim of the process annealing is to restore ductility of cold worked metal.

3. Stress relief annealing:

In stress relief annealing, the metal is heated to a lower temperature about 650 degree and is kept at this temperature for some time in the furnace to remove the internal stress of metal followed by slow cooling.
Large castings or welded structures tend to possess internal stresses mainly caused during their manufacturing and uneven cooling.
No phase transformation takes place during stress relief annealing.

Purpose of stress Relief annealing:

The main aim of the stress relief annealing is to remove the internal stresses produced in the metal due to

1. Plastic deformation.
2. Non-uniform cooling
3. Phase transformation

4. Spheroidizing Annealing:

Spheroidizing Annealing process is for high carbon and alloy steel in order to improve their machinability.
In spheroidizing annealing, the steel is heated to a temperature below A1 temperature, kept at the

temperature for some time followed by slow cooling. The holding time varies from 15-25 hours. It is mainly used for eutectoid steel and hypereutectic steel such as carbon tool steel, alloy tool steel, bearing steel etc.

This process improves the internal structure of the steel. This can be done by two methods:

1. The material is heated just below the lower critical temperature about 700 degrees and the temperature is maintained for hours and then allowed to cool down.

2. Heating and cooling the material alternatively between the temperature just above and below the lower critical temperature.

Purpose of Spheroidizing Annealing:

1. The main aim of spheroidizing annealing is to improve the machinability of steel.
2. This process reduces harness, uniform structure and prepare the material for quenching.
3. In this process cementite is converted into spherical form.

5. Isothermal Annealing:

In isothermal annealing process, the steel is

heated above the upper critical temperature. When the steel is heated above upper critical temperature, it converts rapidly into austenite structure.
After that, the steel is cooled to a temperature below the lower critical temperature 600 to 700-degree Celsius. The cooling is done by force cooling methods.
This temperature is maintained for a specific time period to produce a homogenous structure in the material.
Isothermal Annealing process is mainly applied to low carbon and alloy steel to improve their machinability.

6. Diffusion Annealing:
This process is known as diffusion annealing as in this process the iron and carbide diffuses with each other. For diffusion higher temperature is required, so the steel is heated above the upper critical temperature. The temperature is nearly about 1000 to 1200 degrees Celsius.
The heat preservation time in this process is nearly 10 to 15 hours.

After diffusion annealing, complete annealing and normalizing are done to refine the tissue.

This process is applied to high-quality steel and segregation of serious alloy steel casting and ingot

Purpose of Diffusion Annealing:
The main purpose of diffusion annealing is to eliminate dendritic segregation and regional segregation. In the solidification process and to homogenize the composition and organization.

7. Incomplete Annealing:
In this incomplete annealing process, the steel is heated to about upper critical temperature. The heat treatment process is obtained by slow cooling after thermal insulation.

Purpose of Incomplete Annealing:
This process is mainly used to obtain spherical pearlite tissues for the hypereutectic steel to eliminate the internal stress, reduce the hardness and improve the machinability.

Advantages of Annealing

The main advantages of annealing are in how the process improves the workability of a material, increasing toughness, reducing hardness and increasing the ductility and machinability of a metal.

The heating and cooling process also reduces the brittleness of metals while enhancing their magnetic properties and electrical conductivity.

Disadvantages of Annealing

The main drawback with annealing is that it can be a time-consuming procedure, depending on which materials are being annealed. Materials with high temperature requirements can take a long time to cool sufficiently, especially if they are being left to cool naturally inside an annealing furnace.

Normalizing

Normalizing is a heat treatment process similar to annealing in which the Steel is heated to about 50 degree Celsius above the upper critical temperature followed by air cooling.

This results in a softer state which will be lesser soft than that produced by annealing.

This heat treatment process is usually carried for low and medium carbon steel as well as alloy steel to make the grain structure more uniform and relieve the internal stresses.

Normalizing carried for accomplishing one or more of the following:

- To refine the grain size.
- Reduce or remove internal stresses.
- Improve the machinability of low carbon steel.
- Increase the strength of medium carbon steel.

- And also to improve the mechanical properties of the medium Carbon Steel.

This heating and slow cooling alters the microstructure of the metal which in turn reduces its hardness and increases its ductility.

Why is Normalizing used?

Normalizing is often performed because another process has intentionally or unintentionally decreased ductility and increased hardness. Normalizing is used because it causes microstructures to reform into more ductile structures. This is important because it makes the metal more formable, more machinable, and reduces residual stresses in the material that could lead to unexpected failure.

Difference between Annealing and Normalizing

S.no.	Annealing	Normalizing
1.	Steel parts are gradually cooled in a furnace.	Steel parts are gradually cool in still air.
2.	Comparatively lower yield point, Ultimate Tensile strength, and impact strength.	The comparatively higher yield points ultimate tensile strength and impact strength.

3.	Comparatively soft and easily machinable.	Comparatively less soft.
4.	Low hardness. BHN ranges from 125 to 220 BHN.	Relatively harder. BHN ranges from 140 to 245 BHN.
5.	Highly ductile and percentage of elongation is more.	The less ductile and relative percentage of elongation is less

The Normalizing Process

There are three main stages to a normalizing process.

1. Recovery stage
2. Recrystallization stage
3. Grain growth stage

Recovery Stage

During the recovery stage, a furnace or other type of heating device is used to raise the material to a temperature where its internal stresses are relieved.

Recrystallization Stage

During the recrystallization stage, the material is heated above its recrystallization temperature, but below its melting temperature. This causes new grains without pre-existing stresses to form.

Grain Growth Stage

During the grain growth, the new grains fully develop. This growth is controlled by allowing the material to cool to room temperature via contact with air. The result of completing these three stages is a material with more ductility and reduced hardness. Subsequent operations that can further alter mechanical properties are sometimes carried out after the normalizing process.

Common Applications for Normalizing

Normalizing is used in many different industries for many different materials. Examples include:

- Ferritic stainless-steel stampings in the automotive industry may be normalized following the work hardening that occurs during their forming process.
- Nickel-based alloys in the nuclear industry may be normalized following the thermal microstructure alteration that occurs following welding.
- Carbon steel may be normalized after it is cold-rolled to reduce the brittleness caused by work hardening.

Hardening

Hardening is metallurgical metalworking process used to increase the hardness of a metal. The hardness of a metal is directly proportional to the uniaxial yield stress at the location of the imposed strain. A harder metal will have a higher resistance to plastic deformation than a less hard metal.

Process of Hardening

- Hall-Petch method
- Strain Hardening
- Solid Solution Hardening
- Precipitation Hardening
- Martensitic Hardening

Hall-Petch Method

The Hall–Petch method, or grain boundary strengthening, is to obtain small grains. Smaller grains increases the likelihood of dislocations running into grain boundaries after shorter distances, which are very strong dislocation barriers.

Strain Hardening

In work hardening (also referred to as strain hardening) the material is strained past its yield point, e.g. by cold working. Ductile metal becomes harder and stronger as it's physically deformed. The plastic straining generates new dislocations.

Solid Solution Hardening

In it, a soluble alloying element is added to the material desired to be strengthened, and together they form a “solid solution”.

Precipitation Hardening

Precipitation hardening (also called *age hardening*) is a process where a second phase that begins in solid solution with the matrix metal is precipitated out of solution with the metal as it is quenched, leaving particles of that phase distributed throughout to cause resistance to slip dislocations.

Martensitic Hardening

Martensitic transformation, more commonly known as quenching and tempering, is a hardening mechanism specific for steel. The steel must be heated to a temperature where the iron phase changes from ferrite into austenite, i.e. changes crystal structure from BCC (body-centered cubic) to FCC (face-centered cubic).

Hardening is carried to accomplish the following:

- To reduce the grain size.
- Obtain maximum hardness.
- Reduce ductility to the minimum.
- To increase the wear resistance of Steel.
- Improve the magnetizing properties.

HARDENABILITY

Introduction

The **hardenability** of a metal alloy is the depth to which a material is hardened after putting it through a heat treatment process. It should not be confused with hardness, which is a measure of a sample's resistance to indentation or scratching.

We can also say that the ability of steel to form martensite* on quenching is referred to as the hardenability. Martensite is a very hard form of steel crystalline structure. The hardenability should not be confused with the hardness of the metal.

Hardness	Hardenability
The hardness of the metal Is the measure of a sample's resistance to indentation or scratching.	Hardenability refers to its ability to be hardened to a particular depth under a particular set of conditions.

Determination of Hardenability

There are two methods to determine hardenability of a metal:

- Grossman's Method
- Jominy end quench method

Grossman's Method

• In Grossman's method, we use round bars of different diameters.

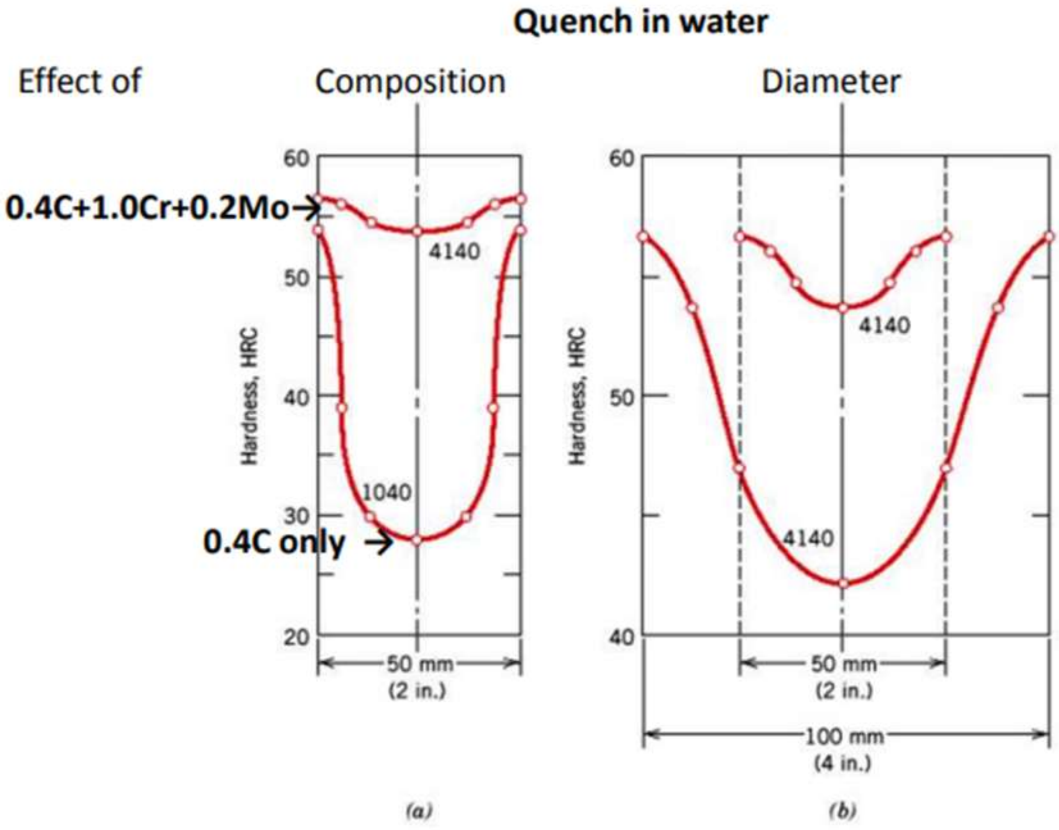
• These bars are quenched in a suitable quenchant.

• Further, we determine the critical diameter (dc) which is the maximum diameter of the rod which produced 50% martensite on quenching.

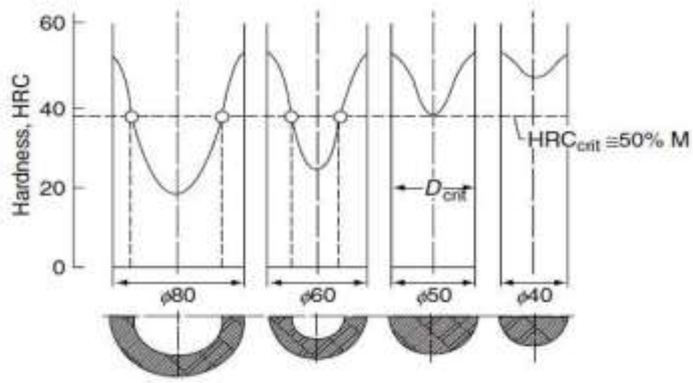
• The ideal diameter (DI) is then determined from the curve.

• This type of experiment requires multiple austenitization and quenching treatments on specimens of varying diameter just to quantify the hardenability of a single material.

Radial hardness profile of cylindrical steel samples of different diameter and composition



Measuring Hardenability



Grossmann's Hardenability concept

Fig:- determination of the critical diameter D_{crit} according to Grossmann.

Jominy End Quench Method

• Grossmans method requires multiple austenitization and quenching treatments on specimens of varying diameter just to quantify the hardenability of a single material.

- An alternative approach is to develop a more convenient standard test method that can be used for relative comparison of hardenability. The Jominy end-quench test is one such approach.
- The jominy end-quench test is specified in ASTM standard A255 and is a widely used method for quantifying hardenability. Its wide use adds to its value, since the utility of empirical relations and data comparison becomes more reliable as more data are accumulated.
- Moreover, Jominy data have been collected on a large enough scale to offer a high degree of statistical certainty for many steels.
- These data have been correlated with measurements and/or calculations of dc.
- By using these correlations, a single Jominy test can be used to estimate dc and DI for a given steel (and austenite grain size).

<u>Principle-</u>

- The hardenability of a steel is measured by a Jominy test:

• A round metal bar of standard size is transformed to 100% austenite through heat treatment, and is then quenched on one end with room-temperature water.

• The cooling rate will be highest at the end being quenched, and will decrease as distance from the end increases.

• The hardenability is then found by measuring the hardness along the bar: the farther away from the quenched end that the hardness extends, the higher the hardenability.

Steps in Jominy End Quench Test-

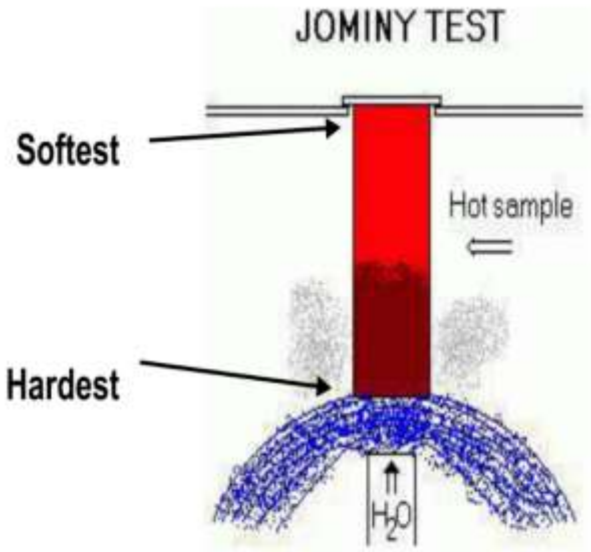
• First, a sample specimen rod either 100mm in length and 25mm in diameter, or alternatively, 102mm by 25.4mm is obtained.

• Second, the steel sample is normalized to eliminate differences in microstructure due to previous forging, and

• Then it is austenitized. This is usually at a temperature of 800 to 900°C.

• Next, the specimen is rapidly transferred to the test machine, where it is held vertically and

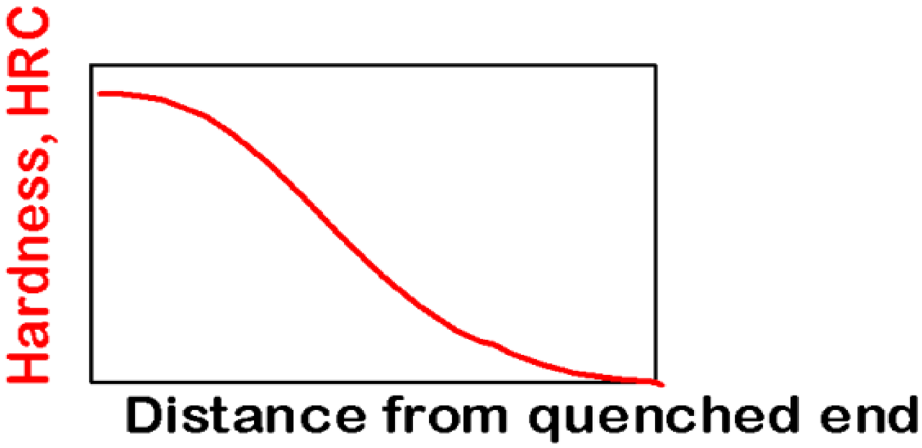
• Sprayed with a controlled flow of water onto one end of the sample. This cools the specimen from one end, simulating the effect of quenching a larger steel component in water. Because the cooling rate decreases as one moves further from the quenched end, you can measure the effects of a wide range of cooling rates from vary rapid at the quenched end to air cooled at the far end.



•The hardness is measured at intervals along its length beginning at the quenched end. Hardness at equal intervals (1 mm or 1/16”) to be checked and noted.

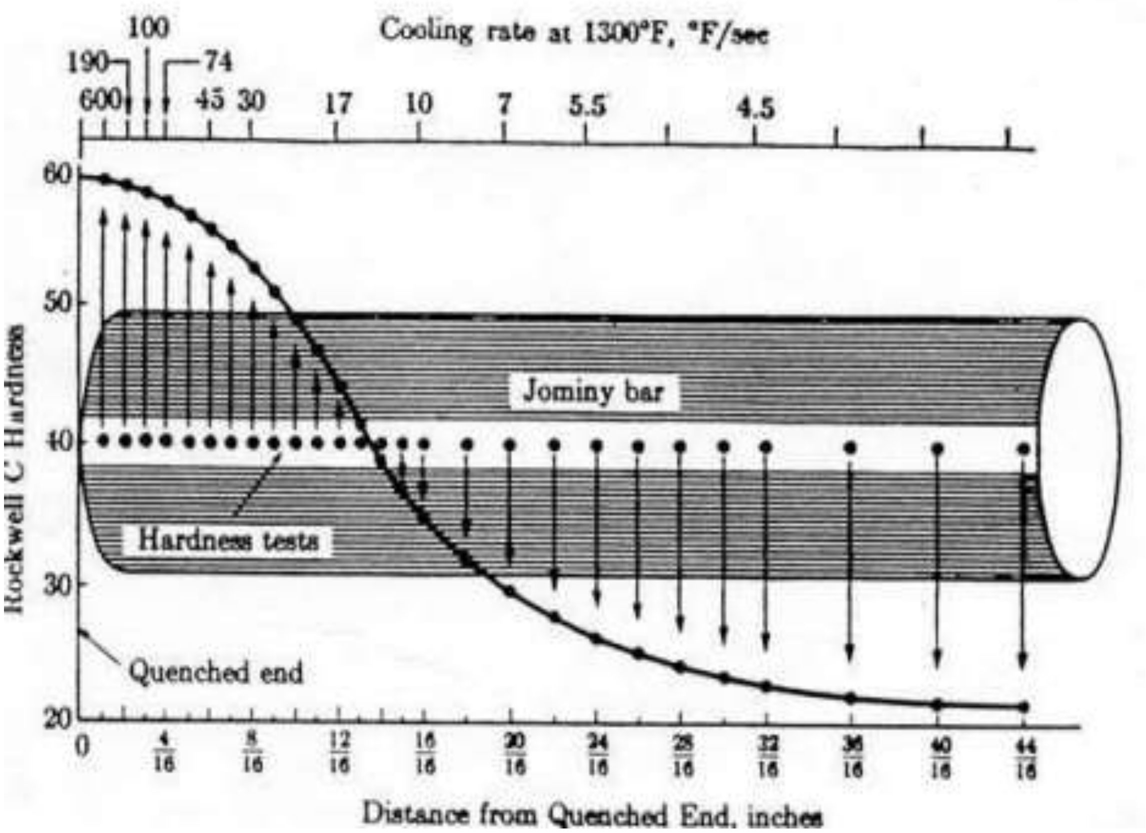
Plotting the result

Plot the resulting data on graph paper with hardness value as ordinate (Y axis) and distance



from the quenched end as abscissa (X axis).

Hardenability Curve



- Jominy distance (distance from the quenched end) do not change with alloying elements as the rate of heat transfer is nearly independent of composition.

- The cooling rate varies throughout the length of the bar, the rate being highest at the lower end which is in direct contact with water.
- The hardness along the length of the bar is then measured at various distances from the quenched end and plotted in a graph.

Jominy Distance (in.)	Cooling Rate (°C/s)
$\frac{1}{16}$	315
$\frac{2}{16}$	110
$\frac{3}{16}$	50
$\frac{4}{16}$	36
$\frac{5}{16}$	28
$\frac{6}{16}$	22
$\frac{7}{16}$	17
$\frac{8}{16}$	15
[illegible]/16	3
$\frac{24}{16}$	2.8
$\frac{28}{16}$	2.5
$\frac{36}{16}$	2.2

Cooling Rates at Different Jominy Distances

- The greater the depth to which the hardness penetrates, the greater the hardenability of the alloy.

Factors affecting Hardenability

• Slowing the phase transformation of austenite to ferrite and pearlite increases the hardenability of steels.

• The most important variables which influence hardenability are

– 1. Austenite grain size

– 2. Carbon content

– 3. Alloying elements

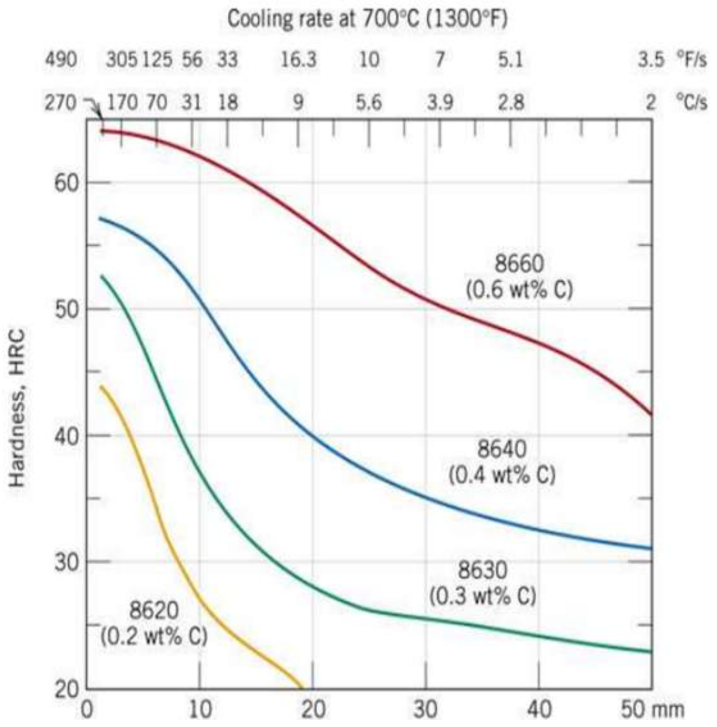
Austenitic Grain Size

- The hardenability increases with increasing austenite grain size, because the grain boundary area which act as nucleating site is decreasing.
- This means that the sites for the nucleation of ferrite and pearlite are being reduced in number, with the result that these transformations are slowed down, and the hardenability is therefore increased.
- The more γ-grain boundary surface the easier it is for pearlite to form rather than martensite
- Smaller γ-grain size → lower hardenability
- Larger γ-grain size → higher hardenability

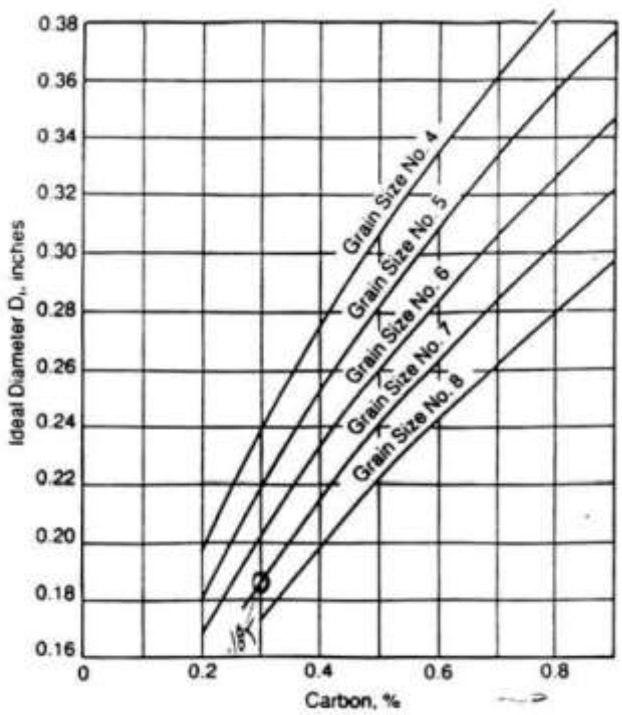
Carbon Content

- Carbon is primarily a hardening agent in steel.
- It also increases hardenability by slowing the formation of pearlite and ferrite.
- But its use at higher levels is limited, because of the lack of toughness which results in greater difficulties in fabrication and, most important, increased probability of distortion and cracking during heat treatment and welding.

• Hardenability of a steel increases with increase in C content→ TTT diagram moves to the right.



Effect of Austenitic Grain size and Carbon Content on D_i



Effect of Alloying Elements

• Most metallic alloying elements slow down the ferrite and pearlite reactions, and so also increase hardenability. However, quantitative assessment of these effects is needed.

• Chromium, Molybdenum, Manganese, Silicon, Nickel and Vanadium all effect the hardenability of steels in this manner. Chromium, Molybdenum and Manganese being used most often.

• Boron can be an effective alloy for improving hardenability at levels as low as .0005%. – Boron is most effective in steels of 0.25% Carbon or less. – Boron combines readily with both Nitrogen and Oxygen and in so doing its effect on hardenability is sacrificed. – Therefore, Boron must remain in solution in order to be affective. – Aluminium and Titanium are commonly added as "gettering" agents to react with the Oxygen and Nitrogen in preference to the Boron.

• The most economical way of increasing the hardenability of plain carbon steel is to increase the manganese content, from 0.60 wt.% to 1.40 wt.%, giving a substantial improvement in hardenability.

• Chromium and molybdenum are also very effective, and amongst the cheaper alloying additions per unit of increased hardenability.

• Boron has a particularly large effect when it’s added to fully deoxidized low carbon steel, even in concentrations of the order of 0.001%, and would be more widely used if its distribution in steel could be more easily controlled.

• Hardenability of a steel increases with addition of alloying elements such as Cr, V, Mo, Ni, W TTT diagram moves to the right.