ME 216 – Engineering Materials II

Chapter 12

Heat Treatment (Part II)

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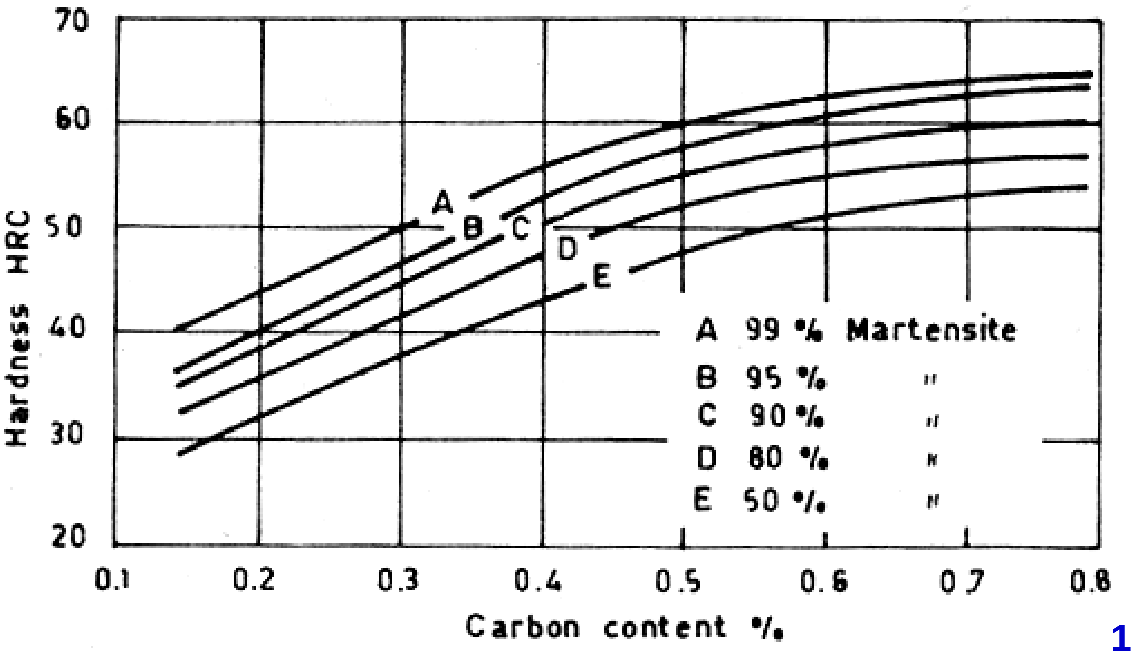
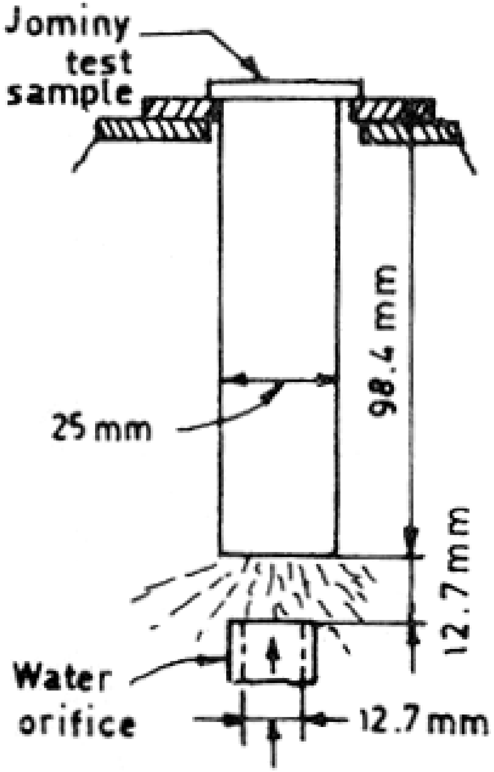
Hardenability

- It is the ability of steel to harden by the formation of martensite on quenching.
- In other words, it determines the depth of hardening obtained on quenching, which is usually specified as the distance below surface where the amount of martensite is reduced to 50 %.
- Hardenability of steel depends on:
  - Quenching medium
  - Method of quenching
  - Composition of steel
  - Section size of steel
- Figure shows relationship between the hardness obtained on quenching, carbon content of steel, and amount of martensite.
- **If the cooling rate is slower than the critical cooling rate**, amount of martensite is reduced, thus **lowering the overall hardness of steel**.

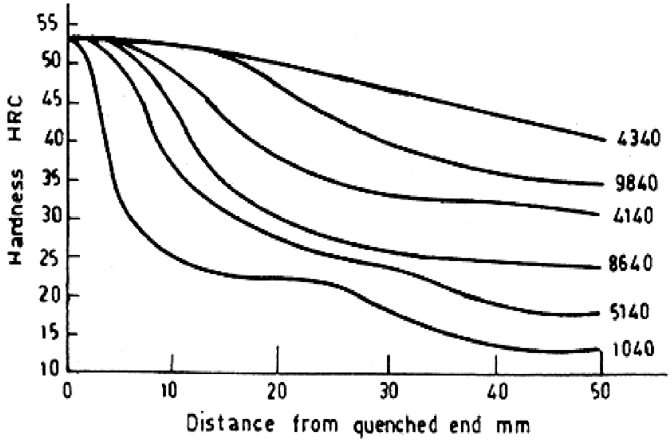


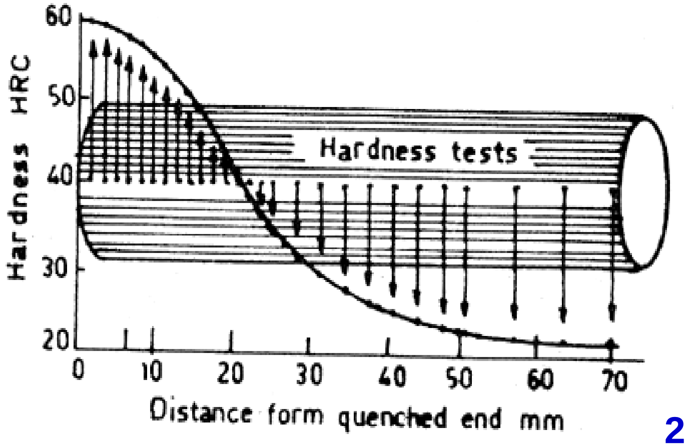
Hardenability Test

- The most widely used method of determining hardenability of steel is **Jominy end-quench test**, standardized by ASTM, SAE and AISI.
- A steel specimen (machined to Ø25 mm & 100 mm long) is heated to austenitizing temp and quickly placed in quenching fixture, in which water is directed against bottom surface until the entire specimen is cool. Upon removal from fixture, two flats (each 0.40 mm deep) are ground.
- Then, Rockwell hardness readings (HRC) are taken at regular intervals from the bottom of specimen and plotted as shown in figure.
- Each location on test piece represents a certain cooling rate, which is the same for given positions regardless of composition as thermal conductivity of all steels is assumed to be the same.
- Thus, each specimen is subjected to a series of cooling rates varying continuously from very rapid at quenched end to very slow at air-cooled end.



- Figure shows the end-quench curves of steels (with 0.40% C but different hardenability).
- They provide **the same max. hardness** at quenched end, but **different trends** through distance from this end.





Quenching Medium

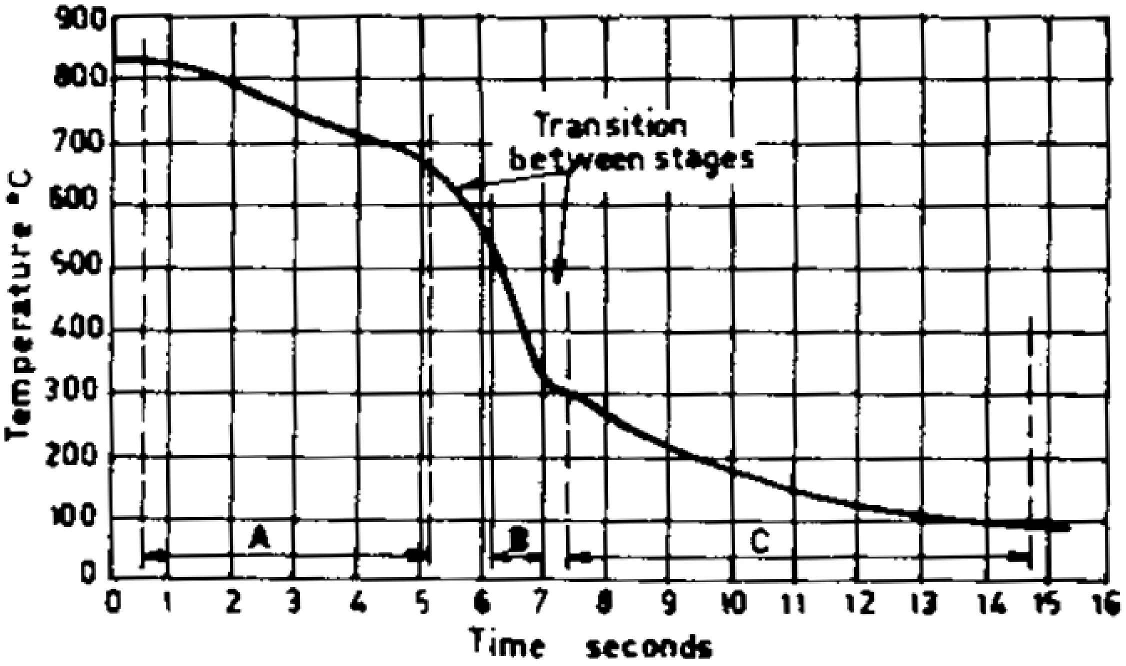
- Structure and hardness resulting from quenching are determined by the actual cooling rate of medium. Characteristics of cooling media and mechanism of heat removal are the controlling parameters.

- Every cooling media has a characteristic cooling curve (like water as shown below). Instead of showing a cst cooling rate throughout quench, the cooling curve shows three stages:

A. **Vapor-Blanket Cooling Stage:** Temp. of the metal is quite high that quenching medium is vaporized at the surface, and a thin stable film of vapor surrounds hot metal. Cooling is by conduction and radiation through gaseous film, and cooling rate is relatively slow since vapor films are poor heat conductors.

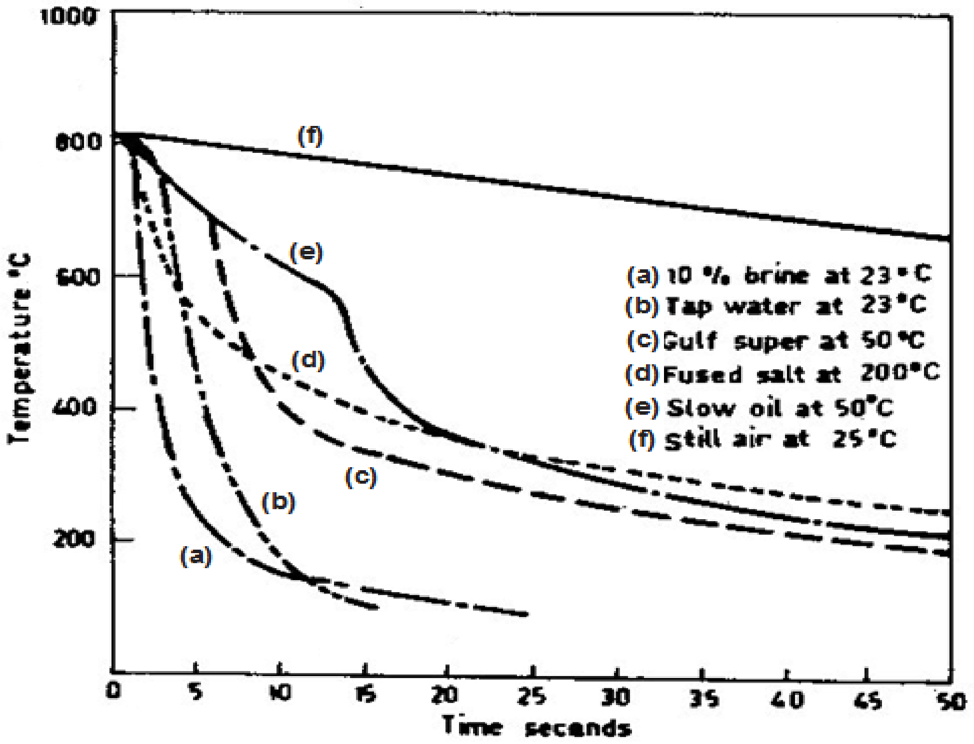
B. **Vapor-Transport Cooling Stage:** This is the fastest stage. It starts when metal is cooled to a temp. at which vapor film is no longer stable. Wetting of metal surface by quenching medium and violent boiling occur. Heat is removed from metal very rapidly as the latent heat of vaporization.

C. **Liquid Cooling Stage:** Rate of cooling is the slowest in this stage. It starts when surface temp. of metal reaches boiling point of the quenching liquid. Vapor no longer forms, so cooling is by conduction and convection through the liquid.



Quenching Medium

- The ideal quenching medium would have high initial cooling rate (to avoid transformation in nose region of TTT diagram) as well as slow cooling rate throughout lower temperature range (to minimize distortion). **Unfortunately, there is no quenching medium that exhibits such ideal properties.**
- Figure shows cooling curves obtained by different media on Ø12.5 mm austenitic stainless steel bar.
- Water and water solutions of inorganic salts have high initial cooling rates through A & B stages, but such high rates persist to low temperatures where distortion and cracking tend to occur. But, oils have longer A & shorter B with slower rate of cooling.
- As temp. of medium rises, cooling rate decreases. This is true for water and brine, but oils show an increase in cooling rate with rise in medium temp.
- Cooling rate is improved by circulation of medium and agitation of workpiece. This wipes off vapor films quickly, thus resulting in faster cooling.
- **Quenching severity** (relative to still water as 1.0) is shown in table for various conditions of quench.



Method of Quenching	Air	Oil	Water	Brine
No circulation	0.02	0.25-0.30	0.9-1.0	2.0
Mild circulation		0.30-0.35	1.0-1.1	2.0-2.2
Moderate circulation		0.35-0.40	1.2-1.3	
Good circulation		0.40-0.50	1.4-1.5	
Strong circulation	0.05	0.50-0.80	1.6-2.0	
Violent circulation		0.80-1.10	4.0	5.0

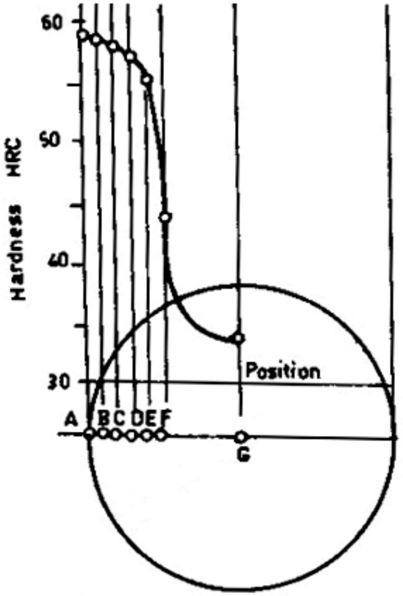
Size & Mass

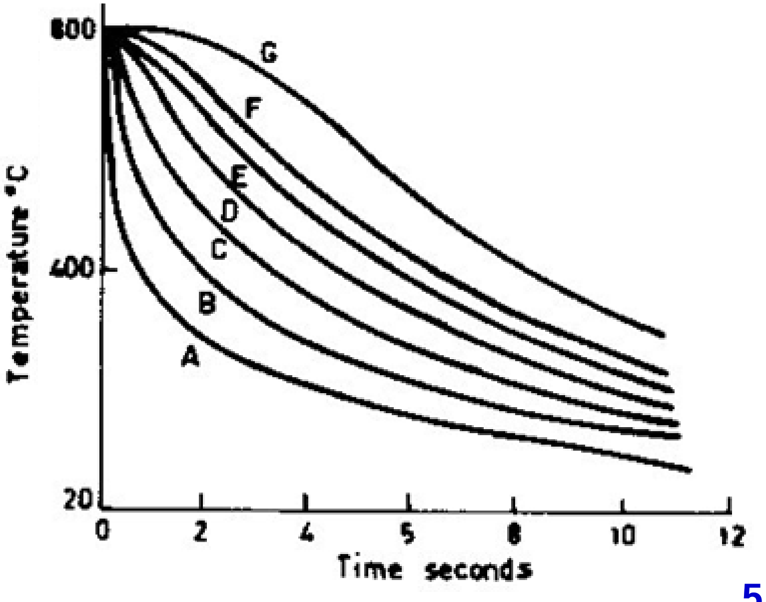
- Only the part surface is in contact with the quenching medium, thus **the ratio of surface area to mass** is an important factor **in determining the actual cooling rate**.
- This ratio is a function of geometric shape of the part, which is the smallest for a spherical part. Thin plates and small diameter wires have a large ratio, and hence rapid cooling rates.
- For a long cylinder (with diameter of **D**, length of **L**, and density of ρ), *surface area of ends is negligible*:
- As seen from the equation, the ratio is inversely proportional to diameter. If the diameter is increased, the ratio decreases, and hence the cooling rate also decreases.

$$\frac{\textbf{\textit{Surface Area}}}{\textbf{\textit{Mass}}} = \frac{\pi \boldsymbol{DL}}{\left[\left(\pi \boldsymbol{D}^2/4\right)\boldsymbol{L}\right]\rho} = \frac{4}{\boldsymbol{D}\rho}$$

- The cooling rate in the interior of a part is less than that at the part surface.
- Figure shows time-temp cooling curves at different positions in a Ø25.4 mm cylinder during a drastic water quench.

  If such a variation in cooling rates exists across the radius of bar during cooling, it is to be anticipated that variations in the hardness would be evident across cross-section of the bar.



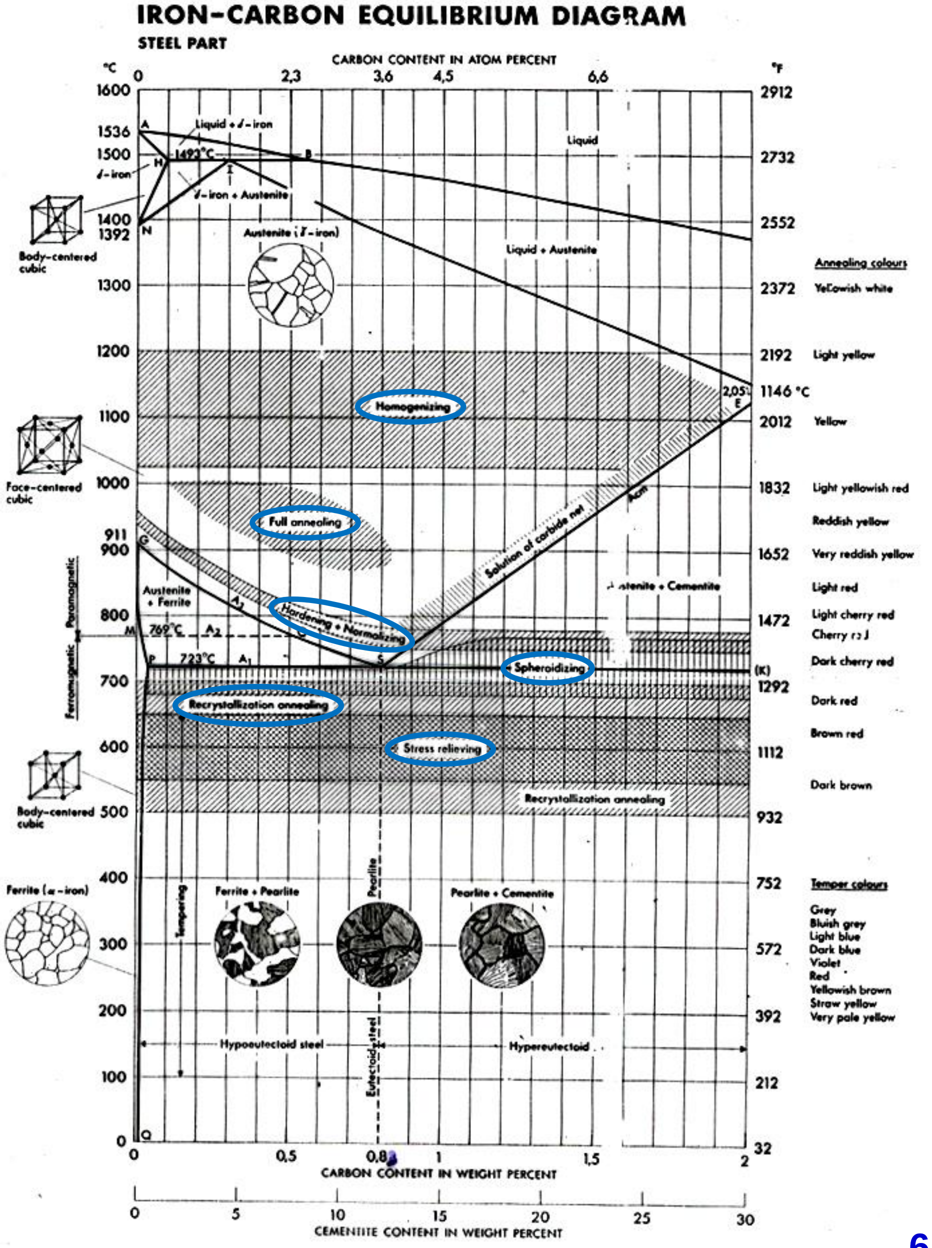


Annealing

- It is usually accomplished by heating steel to slightly above the critical range, holding it there until the part temperature is uniform, and then cooling **slowly**.

- **The purpose of annealing** may be:
  - to refine the grain
  - to induce softness
  - to improve electrical and magnetic properties
  - to homogenize the structure
  - to improve machinability

- **Types of annealing** are as follows:
  1. Spherodizing annealing
  2. Full annealing
  3. Isothermal annealing
  4. Process (recrystallization) annealing
  5. Stress-relief (subcritical) annealing
  6. Quench (homogenizing) annealing
  7. Normalizing



1. Spheroidizing Annealing

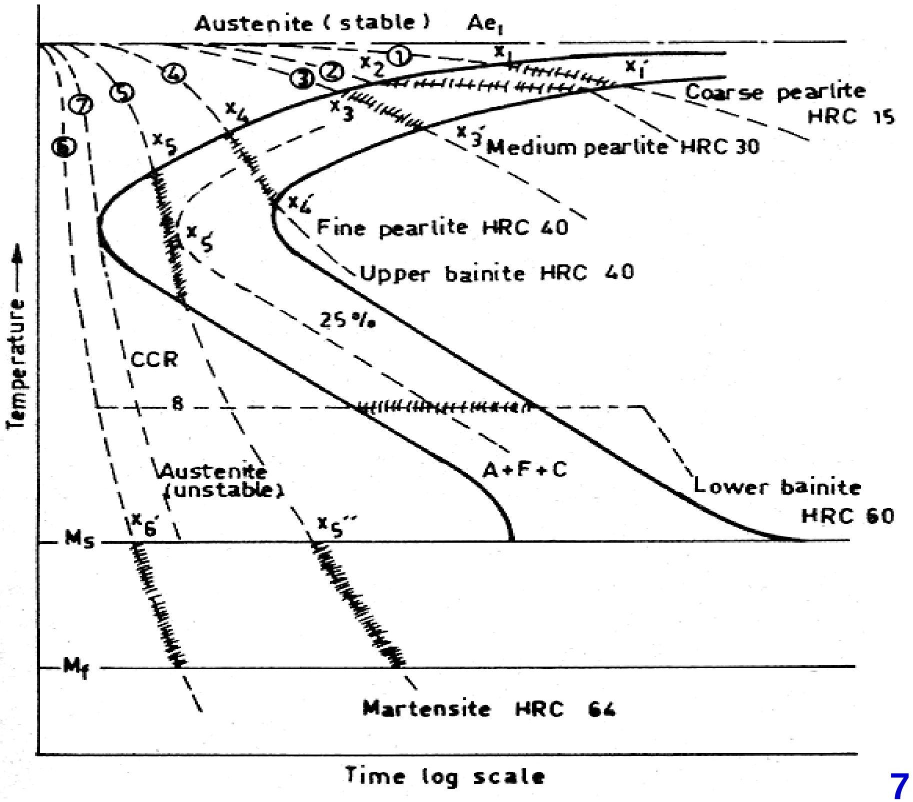
- It produces **the maximum reduction in hardness**.
- The major rule is as follows: austenize (at a temp. not more than 50 °C above **A1**), then transform (at a temp. not more than 50 °C below **A1**).
- For majority of steels, annealing time is **2-6 hours**.
- The resulting microstructure is **spherical carbides embedded in ferrite**.

3. Isothermal Annealing

- Shown by **Curve 2**, it provides a short annealing cycle.
- Steel is heated to 50 °C above the critical range, then quickly transferred to a second furnace at a temp. of about 50 °C below **A1**, held for certain time necessary for complete transformation from austenite to pearlite. After the transformation is complete, the part may be cooled in any manner.
- Isothermal annealing **gives pearlite a more uniform structure** than other annealing processes.
- Fineness of grains depends on transformation temp.

2. Full Annealing

- Illustrated by **Curve 1**, it consists of heating steel to 50 °C above the critical range, then cooling very slowly through its transformation range (preferably in furnace).
- It generally refines the grain size, and **usually performed on high-carbon steels**.



Annealing

4. Process (Recrystallization) Annealing

- It is practiced in **sheet and wire industry** between cold working operations.
- Steel is heated to about 50 °C below **A1**, held about 1 hour, and then cooled slowly.
- New, stress-free grains are formed. Thus, it is essentially the same as *stress-relief annealing*.
- As temperatures involved are low, there is less tendency for steel to scale or decarburize.

5. Stress-Relief (Subcritical) Annealing

- It is useful in removing residual stresses due to heavy machining or cold working processes.
- Applied at a temp. below **A1**, it will not cause phase change, but recrystallization may occur. It only recrystallizes α-grains without affecting cementite morphology.
- Usually applied on **low-carbon steels**. Parts are allowed to cool slowly in furnace so that thermal stresses are not induced.

6. Quench (Homogenizing) Annealing

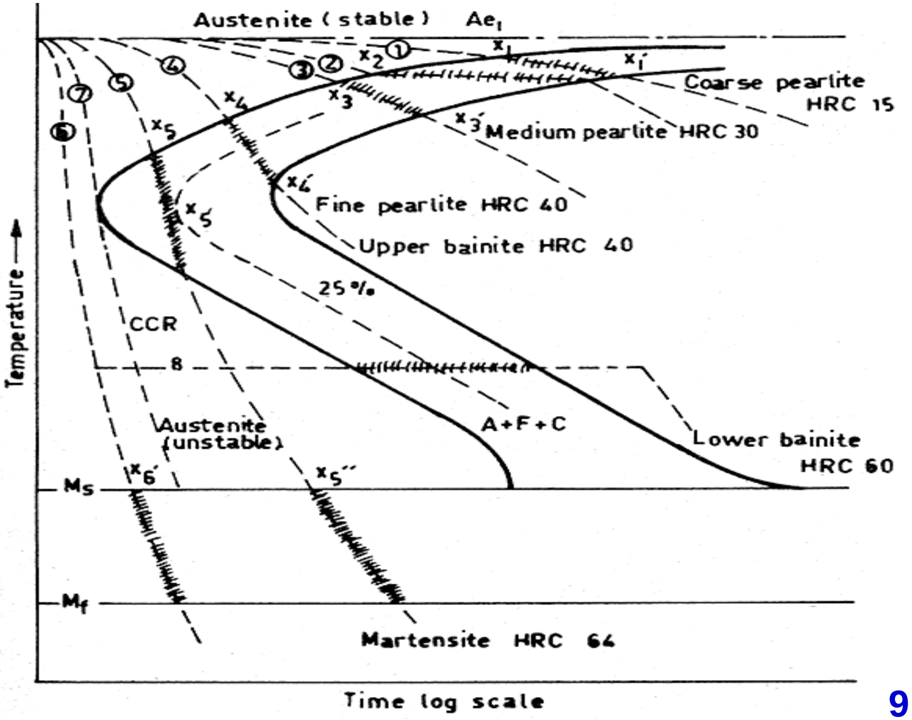
- Used for **austenitic steels only**, and consists of *a homogenizing annealing*.
- Slow cooling will cause carbides to precipitate in austenite grain boundaries, which gives the steel **low impact strength**.
- However, solution treatment around 1000-1100 °C followed by rapid cooling in water will eliminate carbide precipitation, thus **increase toughness**.

7. Normalizing

- Consists of heating steel to hardening temp (50°C above its critical range), holding for 10-20 min, then cooling in free still air.
- It refines the grains, which was coarsened due to forging or welding.
- Applied mainly to **plain medium-carbon steels** and **low alloy steels**.
- May also be used to improve machinability, and modify and refine cast dendritic structures.

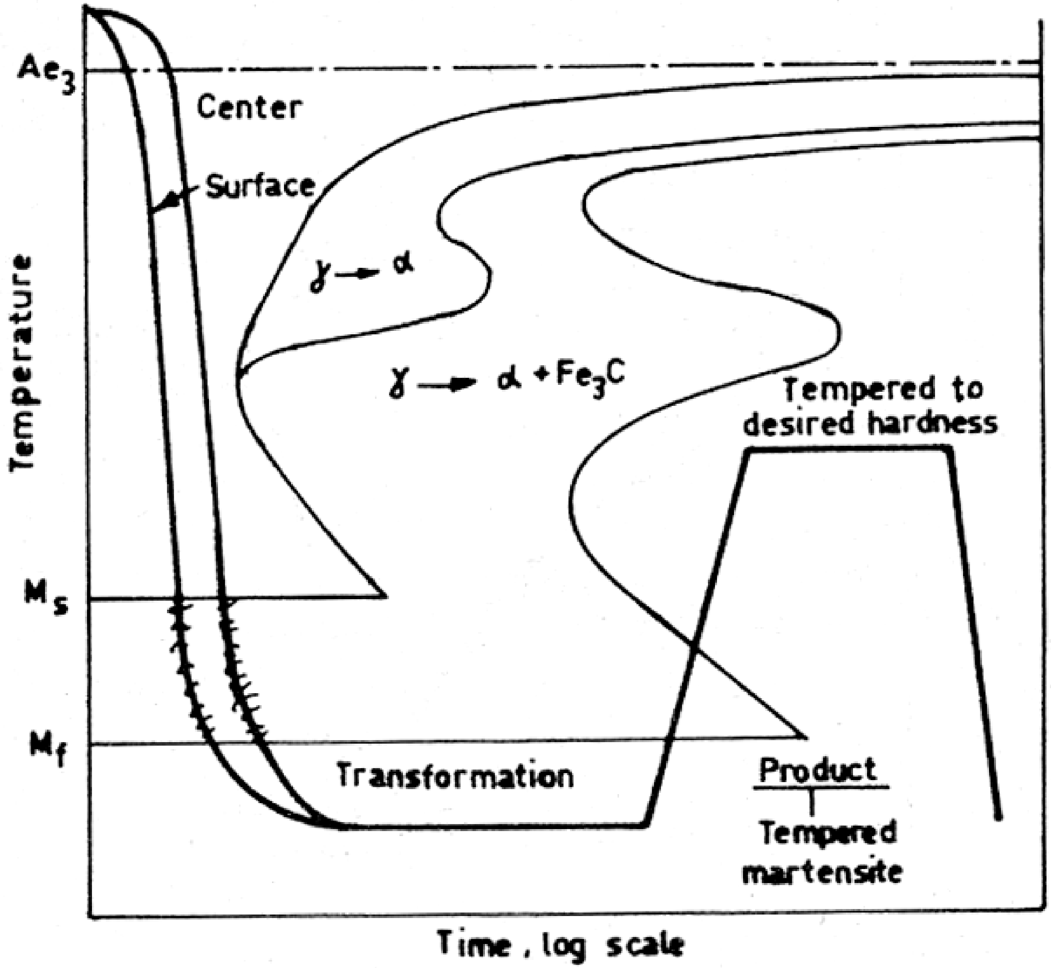
Hardening

- This is the process of heating steel to temp. of 50 °C above its critical range, then cooling it **rapidly**.
- The rate of heating is important. If the part is heated too fast, homogeneous heating cannot be obtained. If the part is irregular in shape, slow heating is more essential to eliminate warping and cracking.
- The heavier the section, the longer must be the heating time to achieve uniform results. Even after reaching the correct temp, sufficient time should be allowed its thickest section to attain a uniform temp.
- **The soaking time in furnace** is 1 hour for every 25 mm in diameter or thickness of the part. **To prevent oxidation and decarburization**, either furnaces should have controlled atmospheres or protective measures (such as burying in cast-iron chips or coke powder) should be carried out.
- The basic purpose of hardening is to produce a fully martensitic structure. For this purpose, a cooling rate faster than critical rate (**Curve 7**) should be selected otherwise transformation continues in pearlite region.
- **The cooling methods** used for hardening depend on:
  - the grade of steel
  - the shape of part
  - the desired properties
- **Three cooling methods** are:
  - Direct quenching
  - Martempering
  - Austempering



1. Direct Quenching

- This is the oldest hardening method, and yet still the most common one.
- Steel is quenched directly from the hardening temp to the room temp, as shown in figure.
- Depending on steel composition, quenching medium can be water, oil, or air.



Hardening

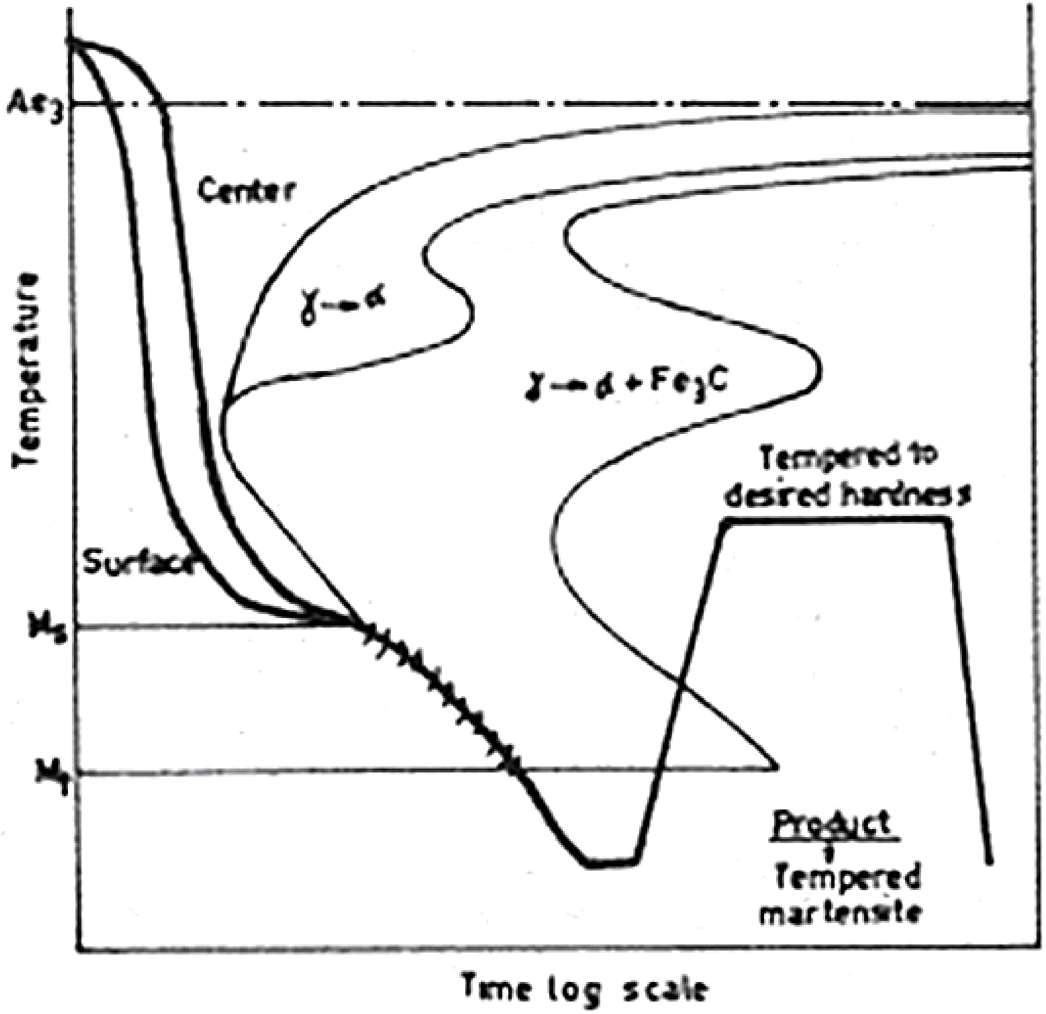
2. Martempering

- In this method, cooling occurs in two stages:
  - First, steel is quenched in a molten salt bath (or a metal bath), kept at a temp just above martensite start (**Ms**). Steel is held there until temp difference between surface and centre is eliminated.
  - Then, it is cooled freely in air, resulting in the formation of martensite.

- Thereby, austenite transforms to martensite simultaneously throughout the cross-section.

- As a result of this, there is less residual stress and minimum distortion.

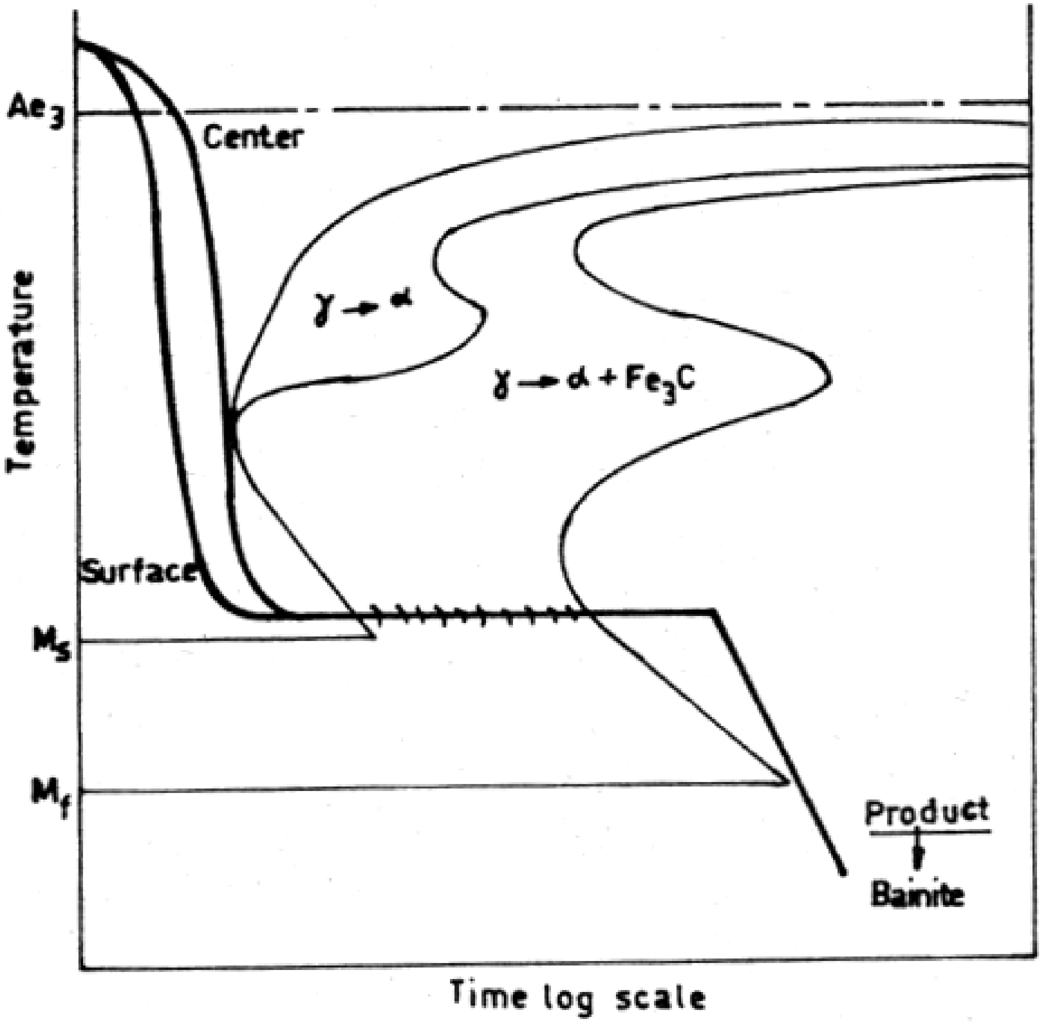
- This method is applicable to **oil-hardening and air-hardening steel grades only**.



Hardening

3. Austempering

- By this method, it is possible to obtain greater toughness than that obtained by conventional hardening and tempering to same hardness.
- *As in the case of martempering*, the part is quenched in salt bath at a temp slightly above martensite start (**Ms**), and kept there until all austenite is transformed to bainite.
- Residual stress and distortion are minimum.
- Cooling takes place freely in air, and resulting hardness depends on temp of salt bath.
- All steels capable of being martempered can also be austempered.
- It is common practice to austemper **low-alloy steels and plain carbon steels**. High-alloy steels can not be austempered due to their very long transformation times.

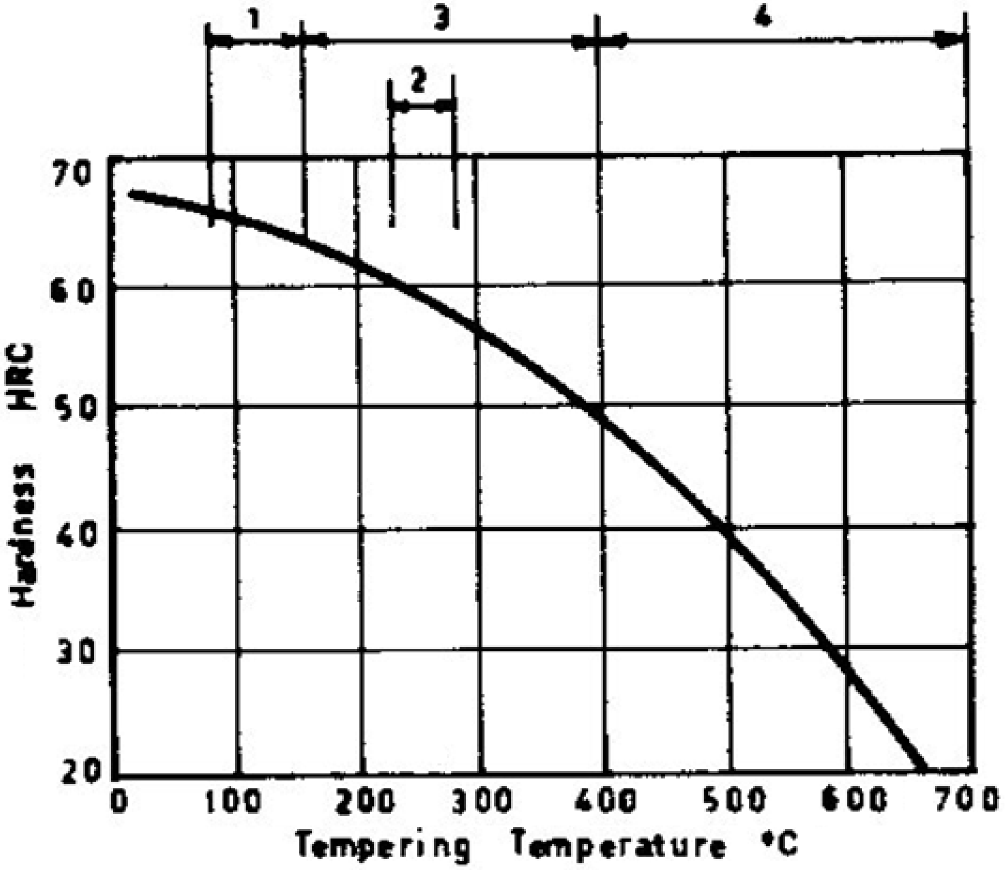


Tempering

- Martensite formed during hardening is too brittle for steel in practical use without tempering. **Tempering** usually results in **an increase in toughness and a simultaneous reduction in hardness**.
- Although tempering softens the steel, it **differs considerably from annealing**:
  - Firstly, tempering does not soften the steel to the extent that annealing would.
  - Secondly, tempering mechanism has a close similarity to those in precipitation hardening.

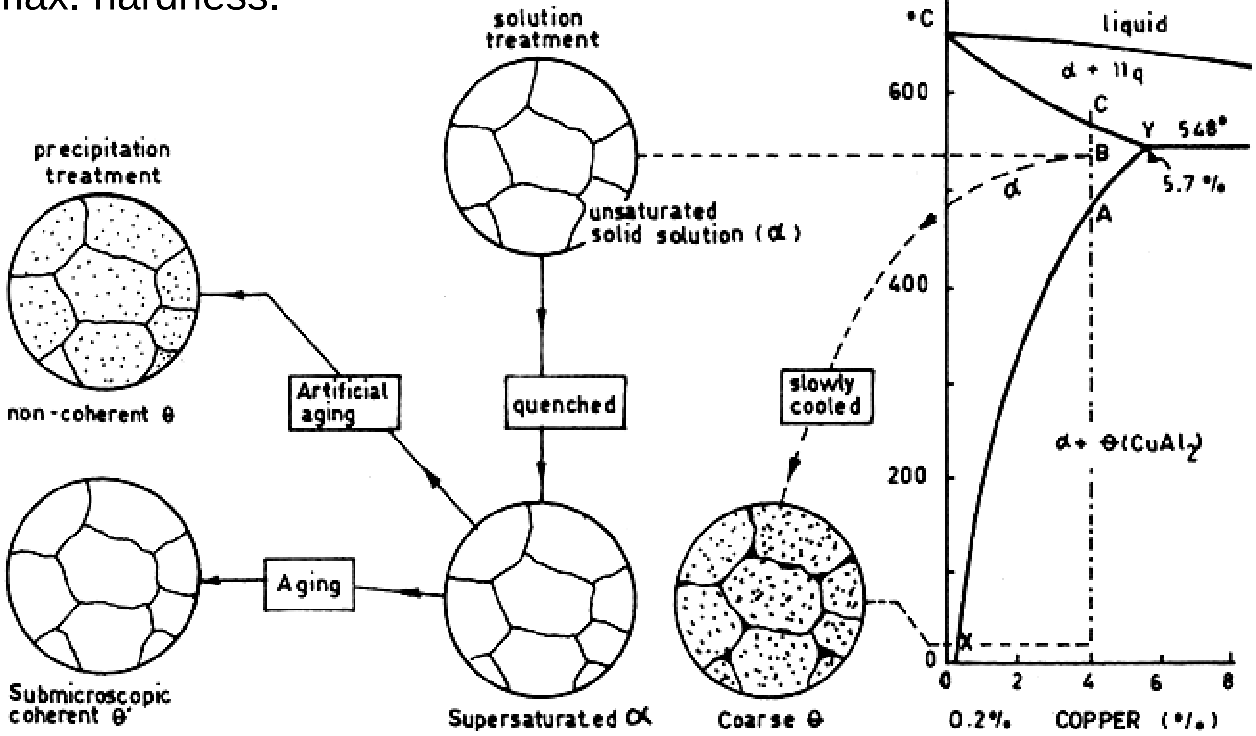
Tempering occurs in four stages:

- **Stage 1 (80 - 160 °C):** Martensite breaks down to a transition precipitate (ε-carbide), resulting in slight dispersion hardening. The product is called "black martensite" due to its darker color.
- **Stage 2 (230 - 280 °C):** It is called "troostite", which is decomposition of retained austenite to bainite and decrease in hardness.
- **Stage 3 (160 - 400 °C):** It is "sorbite", conversion of ε-carbide into cementite, gradually coarsens to give visible particles and rapid softening.
- **Stage 4 (400 - 700 °C):** It is called "spherodite", which refers to carbide changes in alloy steels.
- However, all these products are usually termed as **"tempered martensite"** by metallurgists.



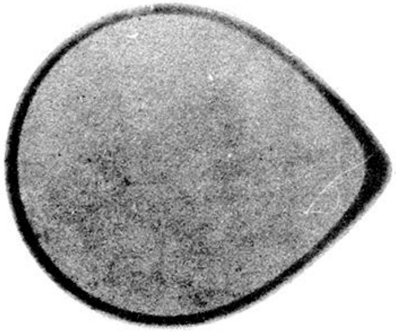
Precipitation (Age) Hardening

- Achieved if there is decreasing solubility of one material in another as temp is reduced. Usually applied to nonferrous industrial alloys, low-carbon unalloyed steels, and some high-alloyed heat-resisting steels.
- Figure shows **the falling solubility curve of Al-Cu alloy**. If an alloy with 4% Cu is heated to 500 °C for a sufficient time, all compounds **($CuAl_2$)** are dissolved to form homogeneous solid solution.
- If slow cooled from 500 °C, it is precipitated as relatively coarse particles, and no hardening is produced.
- If quenched from 500 °C, a supersaturated solid solution is retained at room temp, which is slightly harder but more ductile than slowly cooled case. This is unstable condition, so precipitation of very fine particles occurs at room temp, giving max. hardness.
- Artificial aging at temp up to 200 °C will accelerate the precipitation, but particles will be coarser than natural aging and hardness will be lower.
- Natural aging can be prevented by storing at temp down to -20 °C.
- Instead, insoluble particles (oxides, nitrides, carbides) can be used by P/M process. They are dispersed in metallic matrixes so that their creep properties can be highly improved.



Surface (Case) Hardening

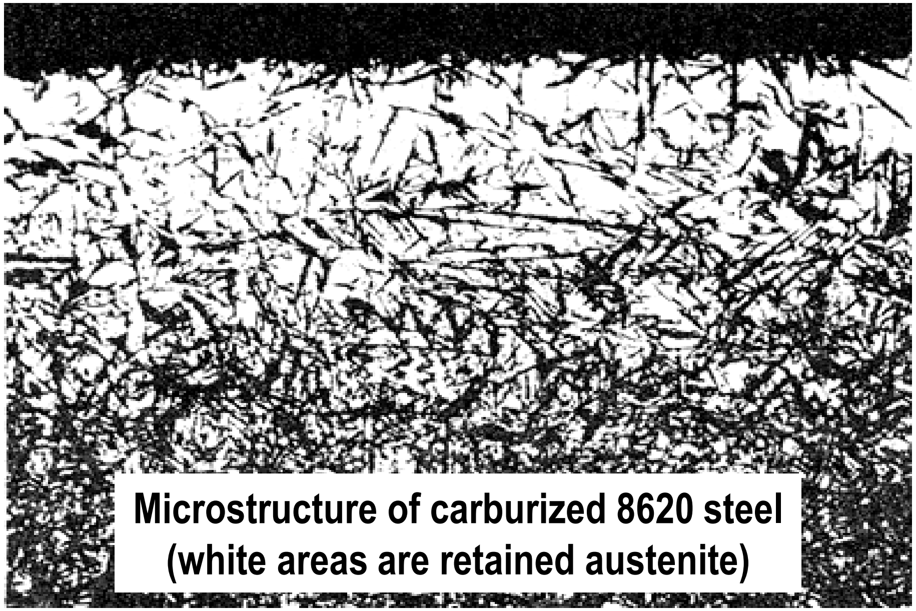
- Numerous industrial applications require a hard wear resistant surface (**the case**) and a relatively soft, tough inside (**the core**).
- There are <u>four principal methods of case hardening</u>:
  1. Carburizing
  2. Nitriding
  3. Flame hardening
  4. Induction hardening
- The first two methods change the chemical composition of steel (by **addition of carbon and nitrogen** in case of carburizing and nitriding, respectively).
- The last two are essentially shallow-hardening methods, and they do not change chemical composition. In such methods, **steel must be capable of being hardened**, and hence it must have 0.3% **C** or higher.



Surface (Case) Hardening

1. Carburizing

- This is the oldest and one of the cheapest method.
- A low carbon steel **(about 0.2% C or lower)** is placed in an atmosphere rich in carbon monoxide (**CO**).
- At usual carburizing temperature (**900 °C**), carbon is absorbed by metal to form a solid solution with iron, and converts the outer surface into high-carbon steel.
- As the process continues, carbon gradually diffuses into interior of the part, in which depth of the case depends upon time and temp of the treatment.



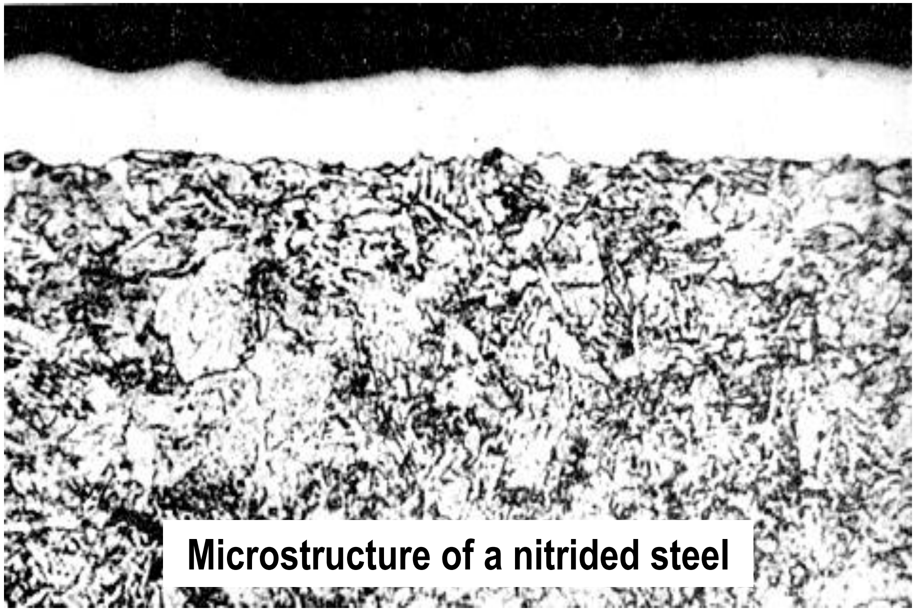
Microstructure of carburized 8620 steel (white areas are retained austenite)

- Commercial carburizing may be accomplished by means of followings:
  - **Pack carburizing:** The part is surrounded by a carburizing compound (charcoal or coke) and 20% barium carbonate (**$BaCO_3$**) as an energizer. It is a long process, and used for large parts to produce fairly thick cases of **0.75-4 mm** in depth.
  - **Gas carburizing:** It may be batch or continuous, and very suitable to production heat treatments. It is done in hydrocarbon fuels (such as natural gas or propane), and case depth is shallow (**0.1-0.75 mm**). It is adapted to small parts, and direct quenching at the end of cycle is possible.
  - **Liquid carburizing:** It is performed in cyanide salt bath, causing carbon and some nitrogen to diffuse into the case. The depth can easily be varied in ranges of **0.5-6.5 mm**. This method is best suited for small and medium size parts, but requires precaution as the cyanide salts are poisonous.

Surface (Case) Hardening

2. Nitriding

- This is a process for case hardening of alloy steels in dissociated ammonia atmosphere around **550 °C**.
- Distortion is minimum due to no phase change.
- The effectiveness of process depends on formation of nitrides in steel by reaction of nitrogen with certain alloying elements (**Al**, **Cr**, **Ti**, **Mo**). Aluminum in range of 1-1.5% is especially suitable in steel.
- Case thicknesses of **up to 0.50 mm** are possible.
- Nitriding develops extreme hardness on part surface. Such hardness **(900-1100 HV)** is considerably higher than that obtained by other case hardening operations.
- Nitrided steels have excellent resistance to fatigue and wear.



Microstructure of a nitrided steel

Surface (Case) Hardening

3. Flame Hardening

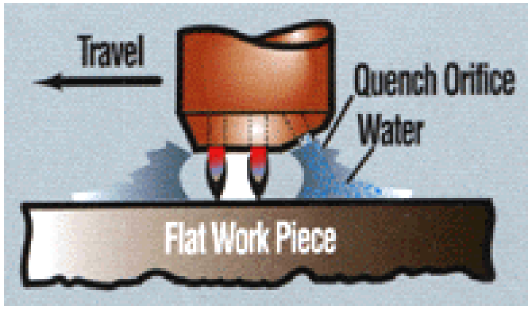
- It is based on rapid heating and quenching of surface to be hardened. Heating is done by oxyacetylene flame, applied for sufficient time to heat the surface above the critical temp range of steel. Integrated with flame head, water connections cool the surface by spraying as soon as desired temp is reached.

- Depth of hardening may be controlled by adjustment of the flame intensity, heating time and speed of travel. Skill is required in adjusting and handling manually operated equipment to avoid overheating the part due to high flame temp. Overheating can result in cracking after quenching.

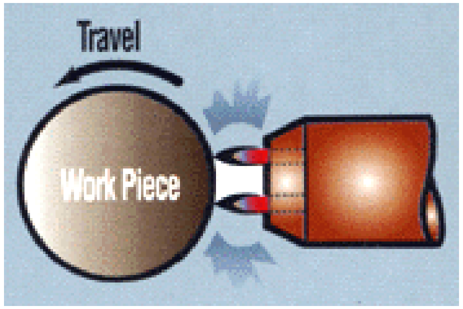
- Flame hardening is adaptable to large pieces. The hardened zone is generally much deeper than that obtained by carburizing, which is in range of **3-7 mm** depth.

- In general, **four methods** are in use for flame hardening *(as illustrated below)*.

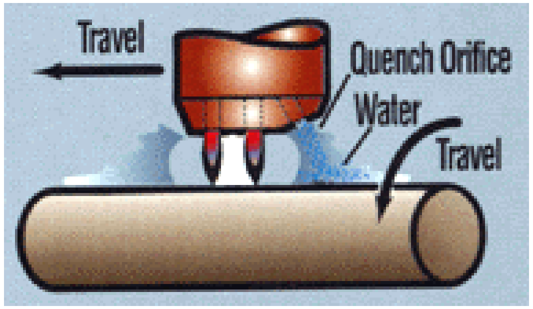
Stationary



Progressive



Spinning



Progressive Spinning

Surface (Case) Hardening

4. Induction Hardening

- It is based on localized heating by currents induced in a part placed in a rapidly changing magnetic field.
- An inductor block (as a primary coil of a transformer) is placed around the part, and a high-frequency current is passed through this block. Heating effect is due to **induced Eddy currents** and **hysteresis losses** in the surface material.

- The inductor block surrounding the heated surface has water connections. As soon as the part has reached to the proper temp, it is automatically spray-quenched under pressure.
- High-frequency induced currents tend to travel at the part surface. This is known as **"skin effect"**, which makes it possible to heat a shallow layer without heating the interior.
- The surface layer is heated instantaneously to **a depth (inversely proportional to the square root of frequency)**. The range of frequencies are usually **10-500 kHz**. Greater case depths may be obtained at each frequency by increasing the time of heating.
- The case obtained by this process is similar to that obtained by flame hardening, and thinner cases are also possible.
- Induction hardening equipment can be fitted into the production line and used by relatively unskilled labor.