ENGINEERING PROPERTIES AND THEIR MEASUREMENTS

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ANNEALING

- **Annealing** is a heat treatment procedure involving heating the alloy and holding it at a certain temperature (annealing temperature), followed by controlled cooling.
- Annealing results in relief of internal stresses, softening, chemical homogenizing and transformation of the grain structure into more stable state.

Stages in Annealing

- **Stress relief** (**recovery**) – a relatively low temperature process of reducing internal mechanical stresses, caused by cold-work, casting or welding.
- During this process atoms move to more stable positions in the crystal lattice. Vacancies and interstitial defects are eliminated and some dislocations are annihilated.
- Recovery heat treatment is used mainly for preventing stress-corrosion cracking and decreasing distortions, caused by internal stresses.

Stages in Annealing (cont.)

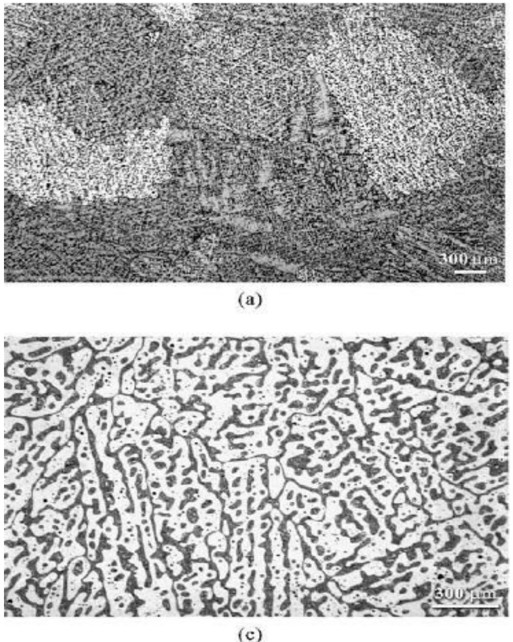
- **Recrystallization** – alteration of the grain structure of the metal.
- If the alloy reaches a particular temperature (recrystallization or annealing temperature) new grains start to grow from the nuclei formed in the cold worked metal. The new grains absorb imperfections and distortions caused by cold deformation. The grains are equi-axed and independent to the old grain structure.

Stages in Annealing (cont.)

- As a result of recrystallization mechanical properties (strength, ductility) of the alloy return to the pre-cold-work level.
- The annealing temperature and the new grains size are dependent on the degree of cold-work which has been conducted. The more the cold-work degree, the lower the annealing temperature and the fine recrystallization grain structure. Low degrees of cold-work (less than 5%) may cause formation of large grains.

Stages in Annealing (cont.)

- Usually the annealing temperature of metals is between one-third to one-half of the freezing point measured in Kelvin (absolute) temperature scale.
- **Grain growth (over-annealing, secondary recrystallization)** –growth of the new grains at the expense of their neighbors, occurring at temperature, above the recrystallization temperature.
- This process results in coarsening grain structure and is undesirable.

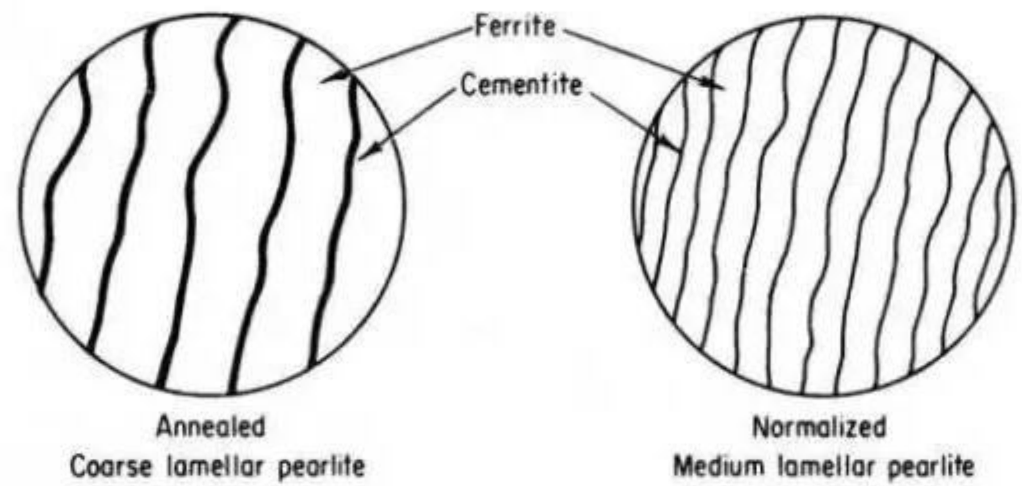


Principle of annealing

- Annealing is the process of heating to 60 degree Celsius to fully convert the structure into austenite and subsequently cooling it very slowly in the heating furnace itself.
- This results in a grain structure of the pearilite with excess of ferrite and cementite. The peocess eliminates internal stresses, reduces hardness, increase ductility, enhance machinability and refines grain structure.
- Different degree of softening can be achieved by slight variation in a annealing temperature,, cooling rate and atmosphere.

Principle of annealing

- For example :- oxidation of the alloys can be minimized by annealing in a sealed container under controlled conditions. This process is called box annealing.



Difference in pearlitic structure due to annealing and normalizing

Hardening

- **Hardening** is a process of increasing the metal hardness, strength, toughness, fatigue resistance
- **Strain hardening (work hardening)** – strengthening by **cold-work** (cold plastic deformation).
- Cold plastic deformation causes increase of concentration of dislocations, which mutually entangle one another, making further dislocation motion difficult and therefore resisting the deformation or increasing the metal strength.

Hardening (cont.)

- **Grain size strengthening (hardening)** – strengthening by grain refining.
- Grain boundaries serve as barriers to dislocations, raising the stress required to cause plastic deformation.
- **Solid solution hardening** – strengthening by dissolving an alloying element.
- Atoms of solute element distort the crystal lattice, resisting the dislocations motion. Interstitial elements are more effective in solid solution hardening,than substitution elements.

Hardening (cont.)

- **Dispersion strengthening** – strengthening by addition of second phase into metal matrix.
- The second phase boundaries resist the dislocations motions, increasing the material strength. The strengthening effect may be significant if fine hard particles are added to a soft ductile matrix (composite materials).
- **Hardening as a result of Spinodal decomposition**. Spinodal structure is characterized by strains on the coherent boundaries between the spinodal phases causing hardening of the alloy.
- **Precipitation hardening** (**age hardening**) – strengthening by precipitation of fine particles of a second phase from a supersaturated solid solution.
- The second phase boundaries resist the dislocations motions, increasing the material strength.

Hardening (cont.)

- The age hardening mechanism in Al-Cu alloys may be illustrated by the phase diagram of Al-Cu system (see figure below)
- When an alloy Al-3%Cu is heated up to the temperature $T_{M,}$ all $CuAl_2$particles are dissolved and the alloy exists in form of single phase solid solution (α-phase). This operation is called **solution treatment**.
- Slow cooling of the alloy will cause formation of relatively coarse particles of $CuAl_2$ intermetallic phase, starting from the temperature $T_{N.}$
- However if the cooling rate is high (**quenching**), solid solution will retain even at room temperature T_F. Solid solution in this non-equilibrium state is called **supersaturated solid solution**.

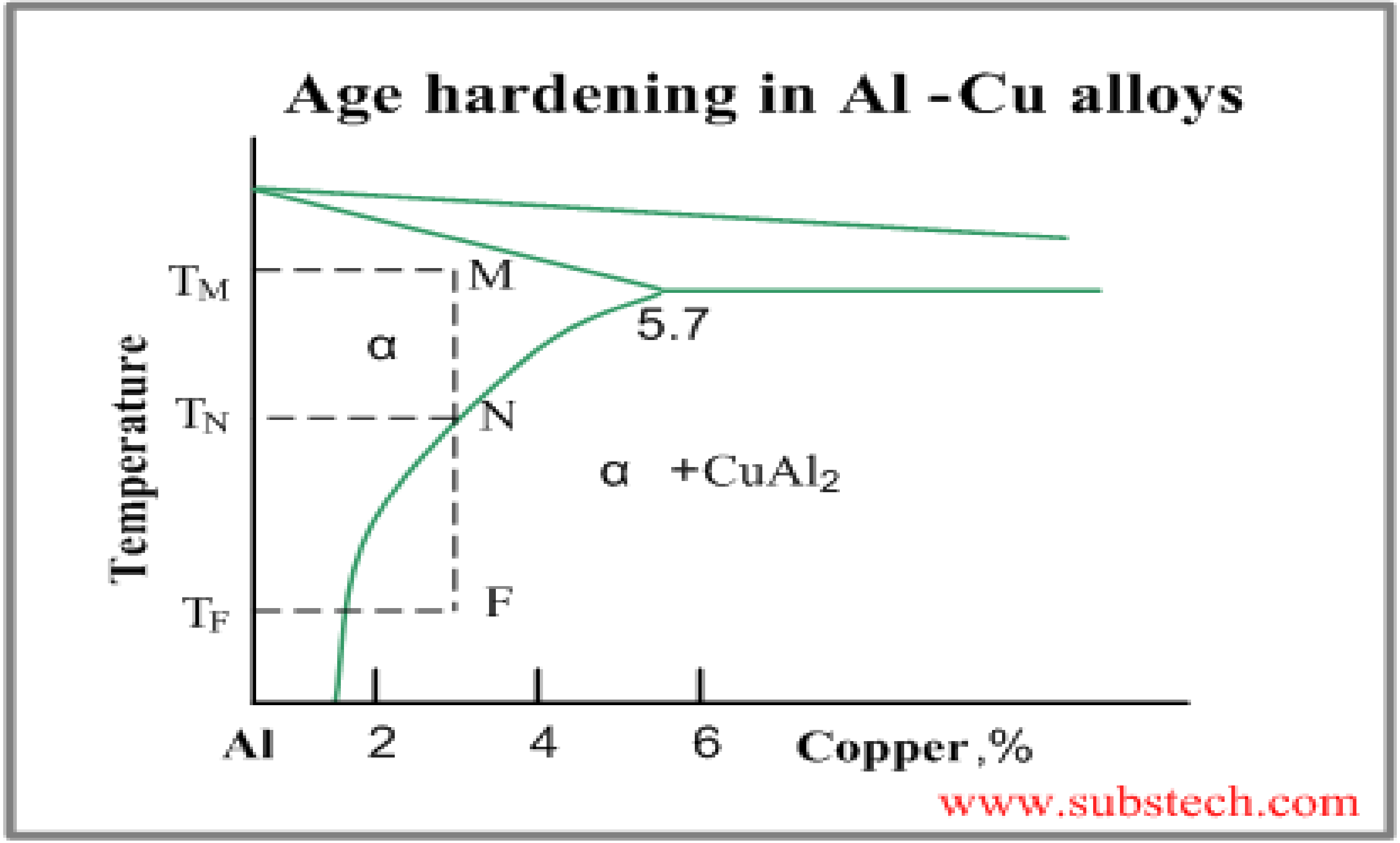
Hardening (cont.)

- Obtaining of supersaturated solid solution is possible when cooling is considerably faster, than diffusion processes.
- As the diffusion coefficient is strongly dependent on the temperature, the precipitation of $CuAl_2$ from supersaturated solution is much faster at elevated temperatures (lower than T_N).This process is called **artificial aging**. It takes usually a time from several hours to one day.

Hardening (cont.)

- When the aging is conducted at the room temperature, it is called **natural aging.** Natural aging takes several days or more.
- Precipitation from supersaturated solid solution occurred in several steps:
- Segregation of Cu atoms into plane clusters. These clusters are called **Guinier-Preston1 zones** (**G-P1 zones**).
- Diffusion of Cu atoms to the G-P1 zones and formation larger clusters, called **GP2** zones or **θ”** phase. This phase is coherent with the matrix .
- Formation of **θ’** phase which is partially coherent with the matrix. This phase provides maximum hardening.

Hardening (cont.)



Principle of hardening

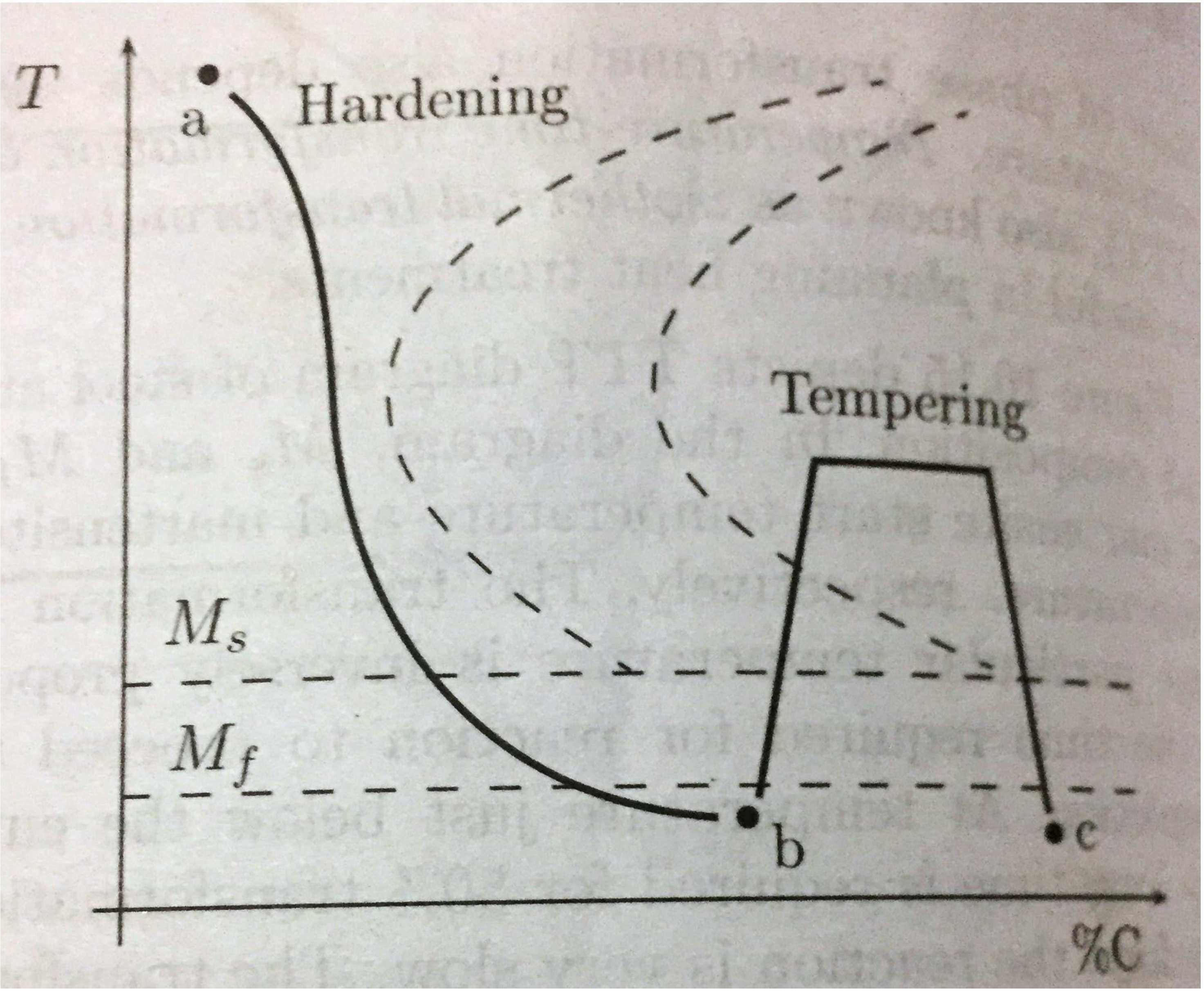
- Hardening involves bringing the steel into austenite range by proper soaking at a temperature greater then 727 degree Celsius and then rapidly cooling it using a quenching media.
- Critical cooling rate (CCR) required for quenching depends upon carbon percentage requires lower CCR.
- Quenching media with decreasing capacity are brine, water, oil, forced air, still air and furnace itself.
- Harden ability is defined as the distance below the surface where the amount of martensite had been reduced to 50%.

Principle of hardening

- Lower grain size promotes the nucleation of pearlite, therefore, harden ability of steel can be increased by increasing the grain size of austenite.
- In dispersion hardening, a dispersion of hard particles in the matrix of a soft phase provides pinning sites for the movement of dislocations.
- In precipitation hardening is suitable for few alloy systems which show significant decreases in solid solubility of one phase into the matrix phase when temperature falls.

Principle of hardening

- The classic example is the duralumin's (96% Al – 4% Cu). For this, precipitations hardening involves heating of the aluminum alloy to around 520 degree Celsius at which the Cu atoms fully dissolves in the Al to give the random substitution solid solution Alfa (α).


T
a
Hardening
Tempering
M_s
M_f
b
c
%C

APPLICATIONS

- Material hardening is required for many applications:
- Construction materials - High strength reduces the need for material thickness which generally saves weight and cost.
- Machine cutting tools (drill bits, taps, lathe tools) need be much harder than the material they are operating on in order to be effective.
- Knife blades – a high hardness blade keeps a sharp edge.
- Bearings – necessary to have a very hard surface that will withstand continued stresses.
- Armor plating - High strength is extremely important both for bullet proof plates and for heavy duty containers for mining and construction.
- Anti-fatigue - (Martensitic) case hardening can drastically improve the service life of mechanical components with repeated loading/unloading, such as axles and cogs.

NORMALIZING

- Normalizing is the process of heating of the material up to austenising temperature range and then cooling at a faster rate in still air.
- Pearlite structure obtained would be of uniformly fine grain size.
- This would results in higher tensile strength (yield point) and hardness than what is possible by annealing.

NORMALIZING

- Normalizing process for steels is defined as heating the steel to austenite phase and cooling it in the air. It is carried out by heating the steel approximately 50 deg C above the upper critical temperature followed by cooling in air to room temperature, or at no greater than 1 bar pressure using nitrogen if the process is being run in a vacuum furnace. Normalizing temperatures usually vary from 810 deg C to 930 deg C. After reaching the soaking temperature the steel is held at that temperature for soaking. The soaking time depends on the thickness of the work piece and the steel composition. Higher temperatures and longer soaking times are required for alloy steels and larger cross sections.

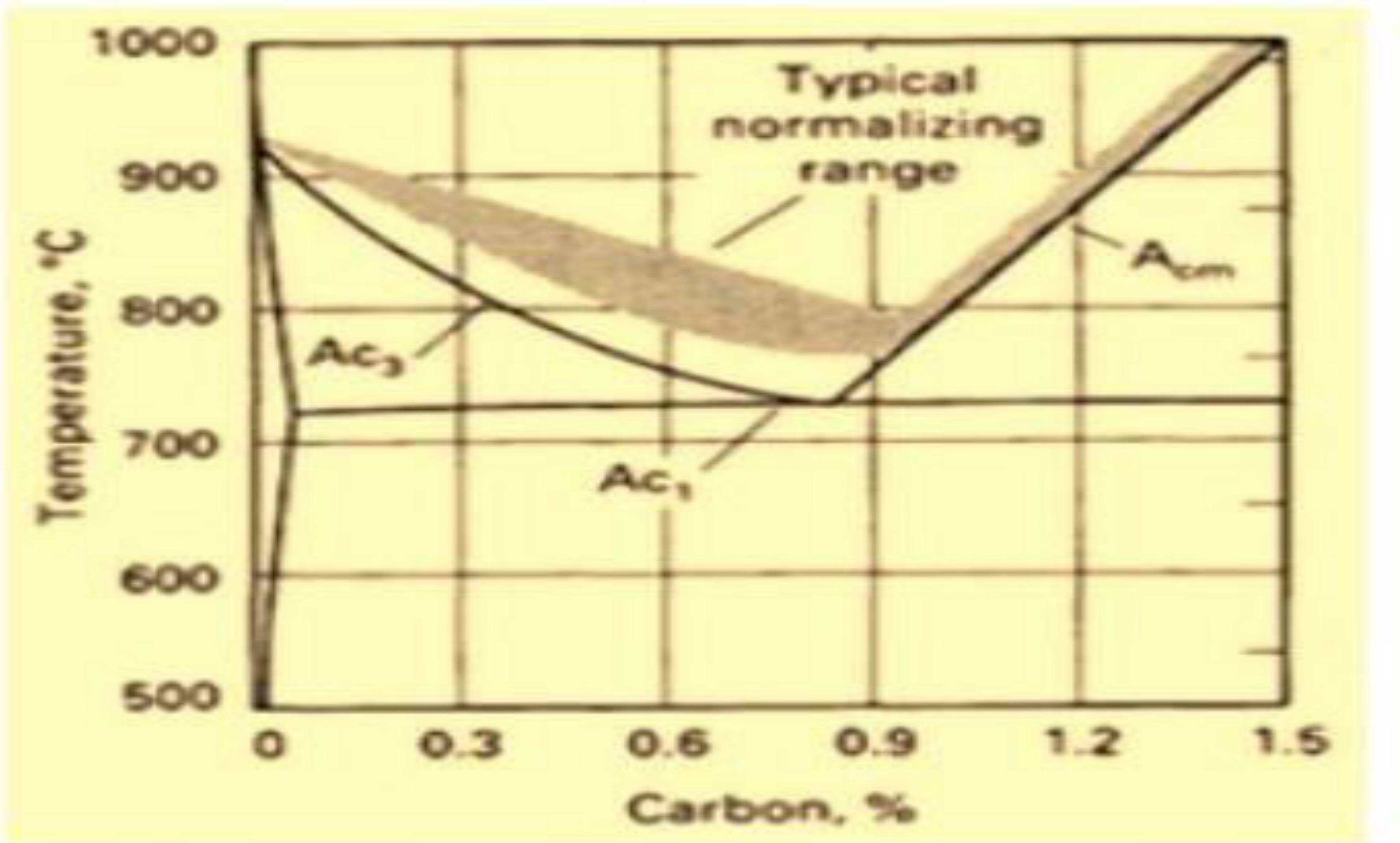


Fig 1 Typical normalizing temperature range for steels

NORMALIZING

- In normalizing, steel is uniformly heated to a temperature which causes complete transformation to austenite. Steel is held at this temperature for sufficient time for the formation of homogenous structure throughout its mass. It is then allowed to cool in still air in a uniform manner. Air cooling results into faster cooling rate when compared with the furnace cooling rate. Thus, the cooling time in normalizing is drastically reduced as compared to annealing.
- Soaking periods for normalizing are usually one hour per 25 mm of thickness of the work piece but not less than 2 hours at the soaking temperature. The mass of the work piece can have a significant influence on the cooling rate and thus on the resulting microstructure. Thin work pieces cool faster and hence are harder after normalizing than the thicker work pieces. This is different than in the case of annealing where the hardness of thin and thicker work pieces is same after furnace cooling.

NORMALIZING

Normalizing is normally done to achieve any one of the following purposes.

- To modify and/or refine the grain structure and to eliminate coarse grained structures obtained in previous working operations such as rolling and forging etc.
- To modify and improve cast dendrite structures and reduce segregation by homogenization of the microstructure.
- To produce a homogeneous micro structure and to obtain desired microstructure and mechanical properties.
- To improve mach inability of low carbon steels
- To improve dimensional stability
- To reduce banding
- To improve ductility and toughness
- To provide a more consistent response when hardening or case hardening.
- To remove macro structure created by irregular forming or by welding.

NORMALIZING

Normalization eliminates internal stresses, strains and improves the mechanical properties of the steel, such as improving its toughness and mach inability. A better ductility can also be obtained without compromising the hardness and strength.

TEMPERING

- Tempering is the process of keeping the material for a longtime at higher temperature. (as shown in previous figure).
- Martensite formed during the quenching process is extremely hard and brittle and lacks toughness.
- To improve the ductility and to remove internal stresses in hardened martensite, tempering is done by heating the quenched steel to a temperature between 200degree Celsius and 400 degree Celsius and then cooling.
- The steel becomes hard an brittle by the quenching process after heating. So high stresses can occur in the structure of the material that cracks are produced and the material slivers to pieces like glass.

TEMPERING

- In order to eliminate those negative effects and give the material the "useful hardness", it is tempered after having been hardened, i.e. it is heated once again. The toughness of the material is increased again at a justifiable decrease of the hardness and strength.
- Tempering temperatures relate to the purpose of use of the workpiece.
- The higher the tempering temperature, the lower the hardness and the tougher the steel.
- When a blank steel is heated, a 0.2 mm thick oxide layer is produced on the surface, this oxide layer becomes discoloured in dependence on the temperature.
- Apart from temperature gauges, the temperature can also be estimated by the colour.

TEMPERING

- **Tempering** is a process of heat treating, which is used to increase the toughness of iron-based alloys. Tempering is usually performed after hardening, to reduce some of the excess hardness, and is done by heating the metal to some temperature below the critical point for a certain period of time, then allowing it to cool in still air.
- The exact temperature determines the amount of hardness removed, and depends on both the specific composition of the alloy and on the desired properties in the finished product.
- Tempering is a heat treatment technique applied to ferrous alloys, such as steel or cast iron, to achieve greater toughness by decreasing the hardness of the alloy.
- The reduction in hardness is usually accompanied by an increase in ductility, thereby decreasing the brittleness of the metal. Tempering is usually performed after quenching, which is rapid cooling of the metal to put it in its hardest state.

TEMPERING

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- Strength: also called rigidity, this is resistance to permanent deformation and tearing. Strength, in metallurgy, is still a rather vague term, so is usually divided into yield strength(strength beyond which deformation becomes permanent), tensile strength (the ultimate tearing strength), shear strength (resistance to transverse, or cutting forces), and compressive strength (resistance to elastic shortening under a load).
- Toughness: Resistance to fracture, as measured by the Charpy test. Toughness often increases as strength decreases, because a material that bends is less likely to break.
- Hardness: Hardness is often used to describe strength or rigidity but, in metallurgy, the term is usually used to describe a surface's resistance to scratching, abrasion, or indentation. In conventional metal alloys, there is a linear relation between indentation hardness and tensile strength, which eases the measurement of the latter