HEAT TREATMENT

Chapter 6

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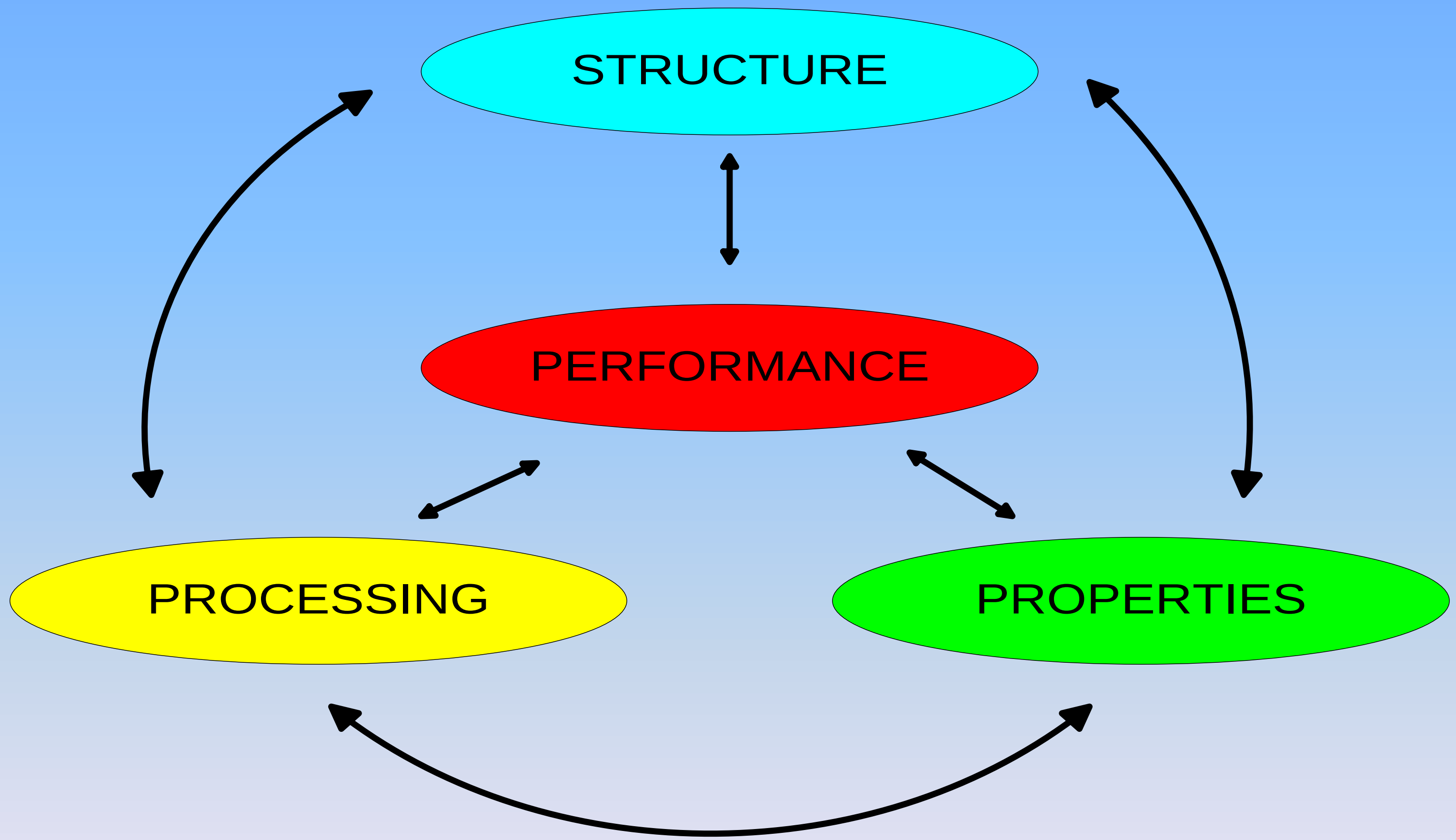
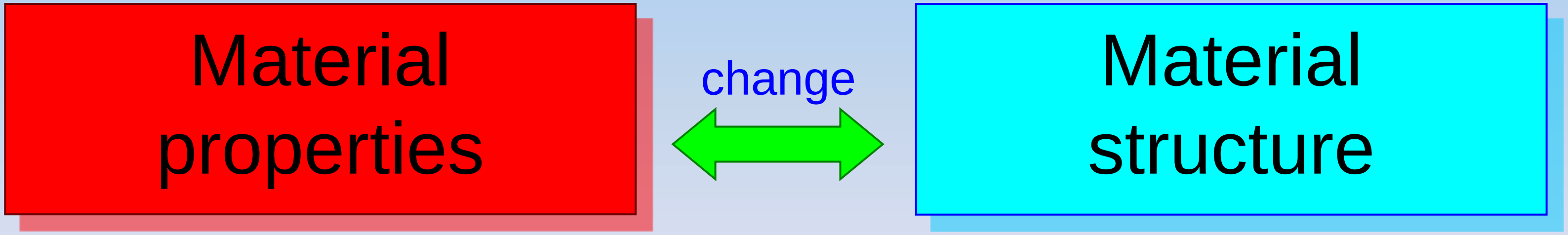
Materials Properties



6.1 Structure –Property Relationships

- Properties and structure can be manipulated and controlled
- Interactive relation to yield improved materials engineering solutions



6.1 What is a Heat Treatment?

- Heat treatment is defined as controlled heating and cooling of materials for the purpose of altering their structures and properties.
- Changes in properties can be introduced with no change in shape
- Heat treatment-term- applies only for processes where heating&cooling are performed intentionally for the purpose of altering properties (not as a side –effect due to environmental/application conditions-such as hot forming or welding)

6.1 Introduction

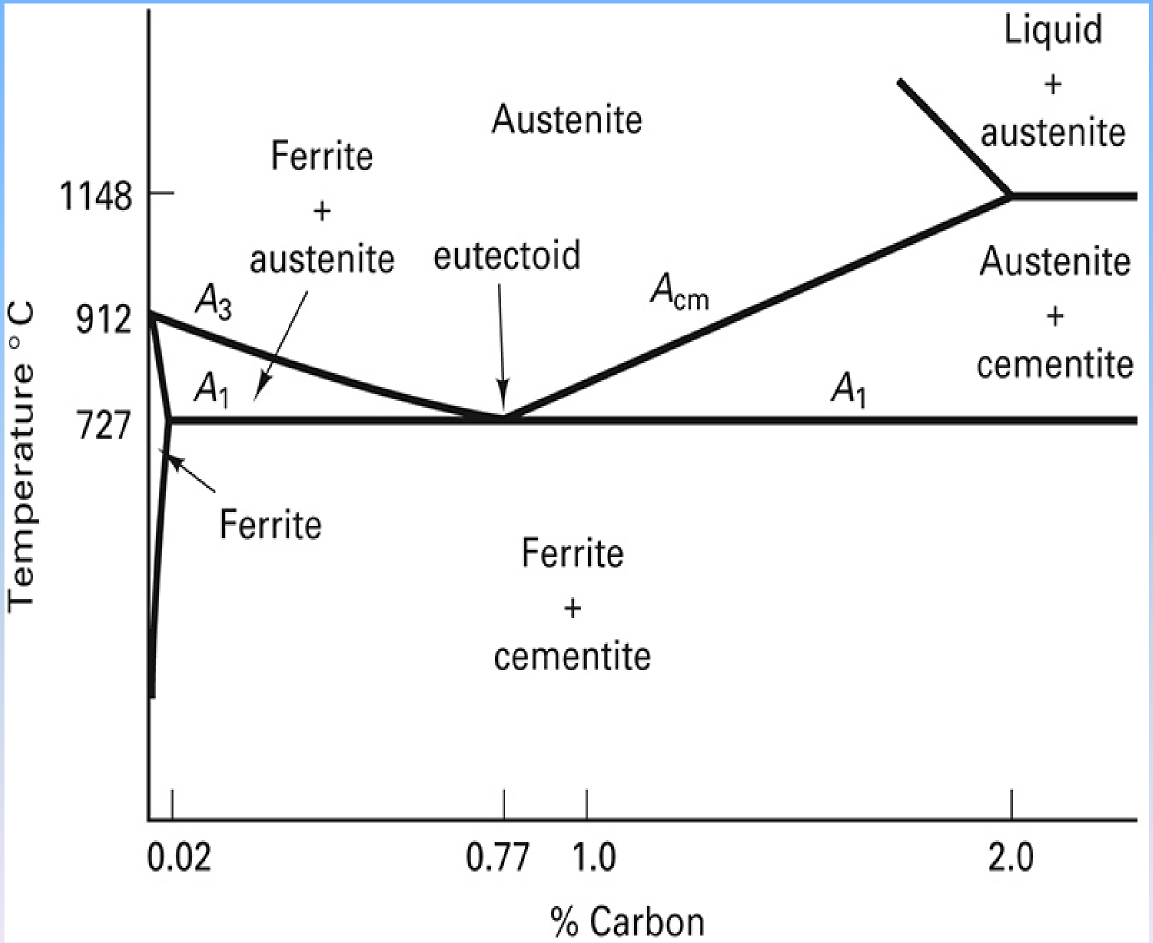
- Heat treatments are integrated with other processes to obtain effective results
- 90% of heat treatments performed on steel and other ferrous alloys

6.2 Processing Heat Treatments

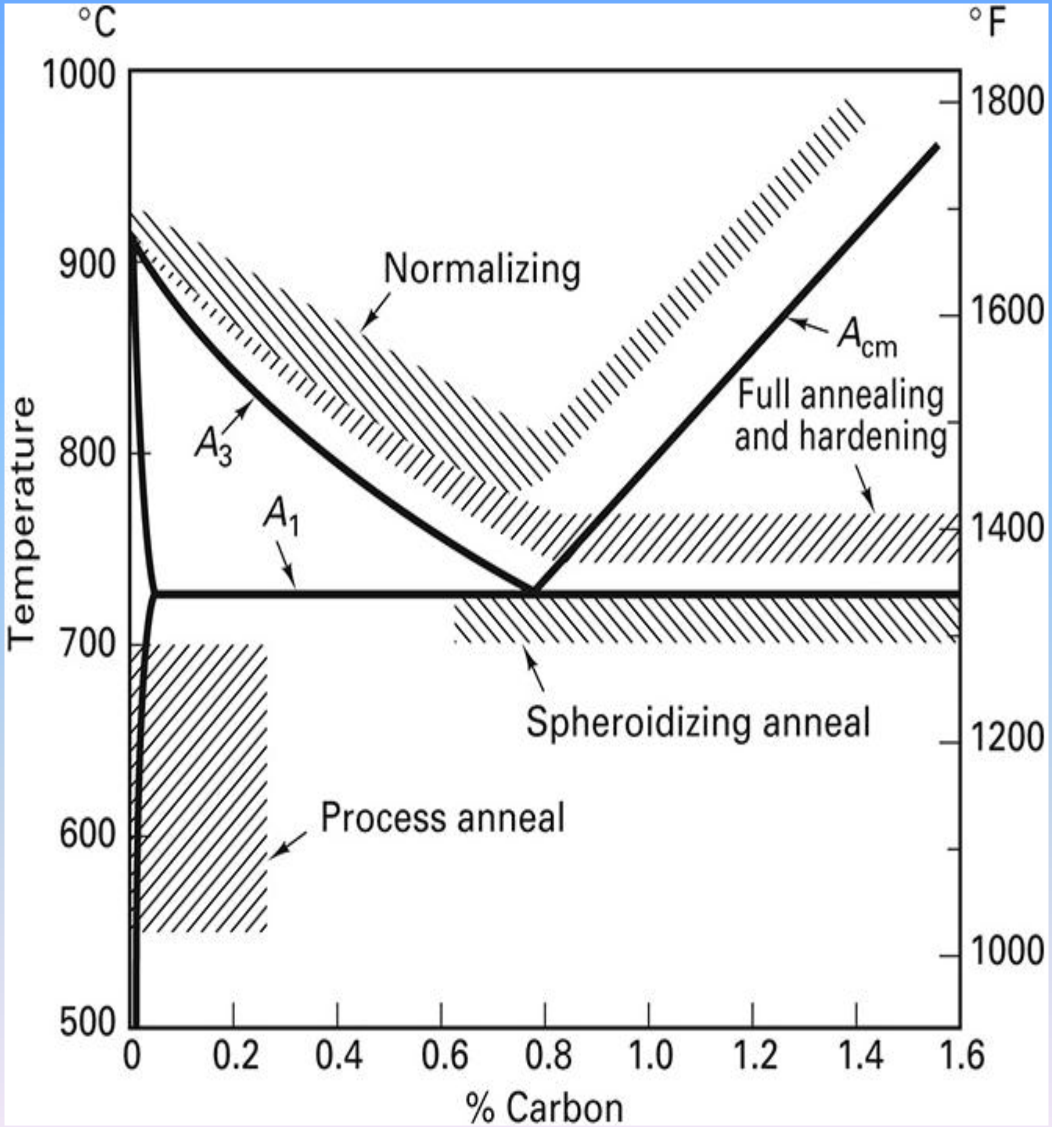
- Most heat treatments are thermal processes that increase strength
- Processing heat treatments are used to prepare the material for fabrication
- Equilibrium phase diagrams are often used to predict resulting structures
- Annealing is a common heat treatment process
  - May be used to reduce strength and hardness
  - Removes residual stresses
  - Improves toughness
  - Restores ductility
  - Refines grain size
  - Reduces segregation, and/or
  - Alters the electrical or magnetic properties of a material

6.2 Eutectoid Transformation of Steel

- Simplified Iron-Carbon phase diagram:



6.2 Process Heat Treatments



6.2 Annealing

- Full Annealing
  - Hypoeutectoid steels are heated to convert the grain structure to homogenous single phase austenite, then control cooled (the cooling results in coarse pearlite with excess ferrite resulting in soft and ductile steel)
  - Hypereutectoid steels undergo a similar process but the structure will be coarse perlite with excess cementite
  - Full anneals are time and energy consuming processes

6.2 Undesirable Features of Annealing

- Time consuming, require considerable energy to maintain the elevated temperatures during the soaking and furnace cooling
- The furnace temperature is changed during the treatment, so the furnace must be reheated to start another cycle

6.2 Process Anneal

- Designed to promote recrystallization and restore ductility of low carbon steels (<0.77%C)
- Steel is heated to a temperature slightly below A1
- Held long enough to attain recrystallization with no phase change
- Recrystallization is induced after a material has been cold worked to reduce strain

6.2 Spheroidizing Annealing

- A spherodization is employed to produce a structure (small globules of cementite dispersed in a ferrite matrix) that enhances machinability or formability of high-carbon steels (>0.60 wt% C)
- Applied to high-carbon (0.60 wt% C) steel
- Heated below A1
- Cementite form globules throughout a ferrite matrix

6.2 Stress-relief Anneal

- Reduces residual stresses in casting, welded assemblies, and cold-formed products
- Materials are heated and then slowly cooled

6.2 Normalizing

- Normalizing is used when the maximum softness is not required and cost savings are desirable
- Normalizing is heating steel to a temperature higher than in annealing (60 °C above line A3 for hypo-eutectoid), held to convert the structure to austenite, and then removed from the furnace and cooled in air (this reduces processing time, furnace time, and fuel and energy use).
  - More cost effective than annealing
  - Cooled in air
- Normalizing vs. annealing
  - In normalizing, cooling will be different in different locations
  - Properties will vary between the surface and interior in normalized steel
  - Lower cost of normalizing is justified if uniform properties are not needed

6.2 Normalizing

- Carbon steel is heated to approximately 55 °C above A3 or Acm for 1 hour;
- The steel completely transforms to austenite
- The steel is then air-cooled, which is a cooling rate of approximately 38 °C (100 °F) per minute
- This results in a fine pearlitic uniform structure, and a more- structure.
- Normalized steel has a higher strength than annealed steel;
- It has a relatively high strength and ductility.

6.3 Heat Treatments Used to Increase Strength

- Six mechanisms for increasing strength
  - Solid-solution strengthening
    - Base metal dissolves other atoms as substitutional solutions or interstitial solutions
  - Strain hardening
    - Increases strength by plastic deformation
  - Grain size refinement
    - Metals with smaller grains tend to be stronger
  - Precipitation hardening
    - Strength is obtained from a nonequilibrium structure
  - Dispersion hardening
    - Dispersing second-phase particles through a base material
  - Phase transformations
    - Heated to form a single phase at an elevated temperature

Heat Treatments for Nonferrous Metals

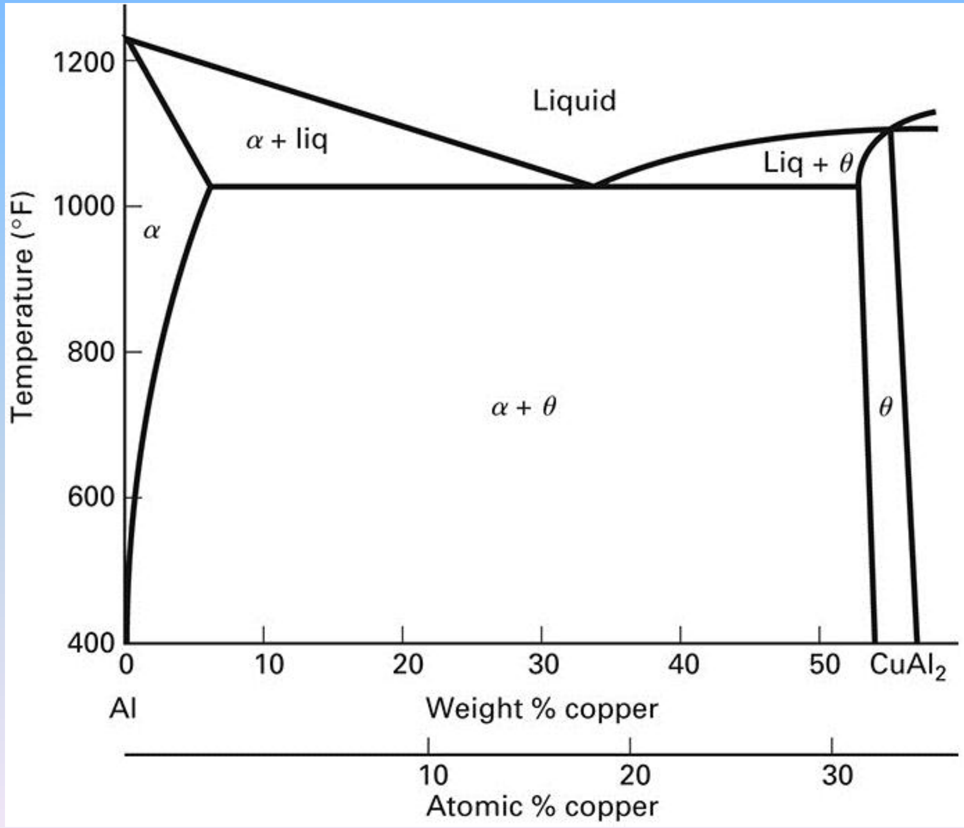
- Nonferrous metals do not have significant phase transitions
- Heat treated for three purposes
  - Produce a uniform, homogenous structure
  - Provide a stress relief
  - Induce recrystallization
- In castings that have been cooled too rapidly, homogenization can be achieved by heating to moderate temperatures and then holding

6.4 Strengthening Heat Treatments for Nonferrous Metals

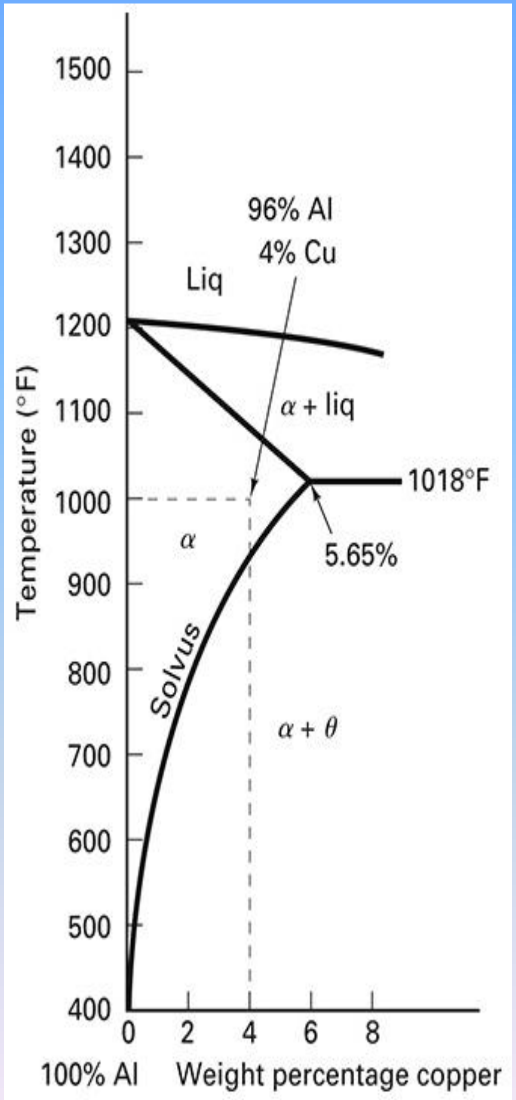
- Precipitation hardening is the most effective mechanism to strengthen nonferrous metals
  - Alloys must exhibit solubility that decreases with decreasing temperature
- When two or more phases exist, the material is dispersion strengthened
- Dislocations can also provide strength
- Precipitation hardening process
  - Heating, quenching, aging

6.4 Precipitation or Age Hardening

- High-Al section of Al-Cu equilibrium diagram
- Coherency-the crystalographic planes of the parent structure remains continuous



6.4 Iron-Thermal Treatment of Al-Cu Alloy



Coherency

- Solute atoms distort or strain lattices
- If the strain exceeds a certain point, the solute atoms can break free and form their own crystal structure
  - Dispersion strengthening
  - Strength and hardness decrease and the material is said to be overaged

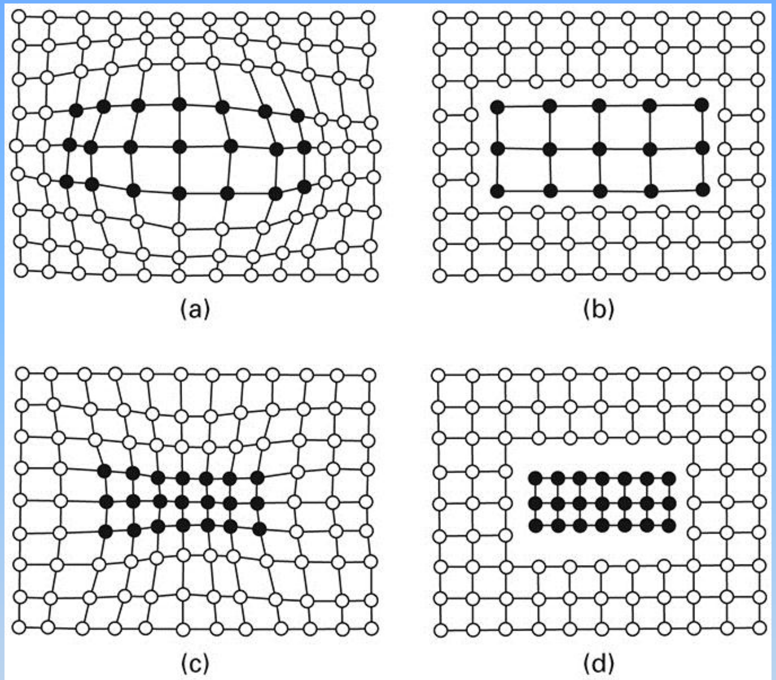


Figure 5-5 Two dimensional illustrations depicting a) a coherent precipitate cluster where the precipitate atoms are larger that those in the host structure, and b) its companion overaged or discrete second phase precipitate particle. Parts c) and d) show equivalent sketches where the precipitate atoms are smaller than the host.

Aging Curves

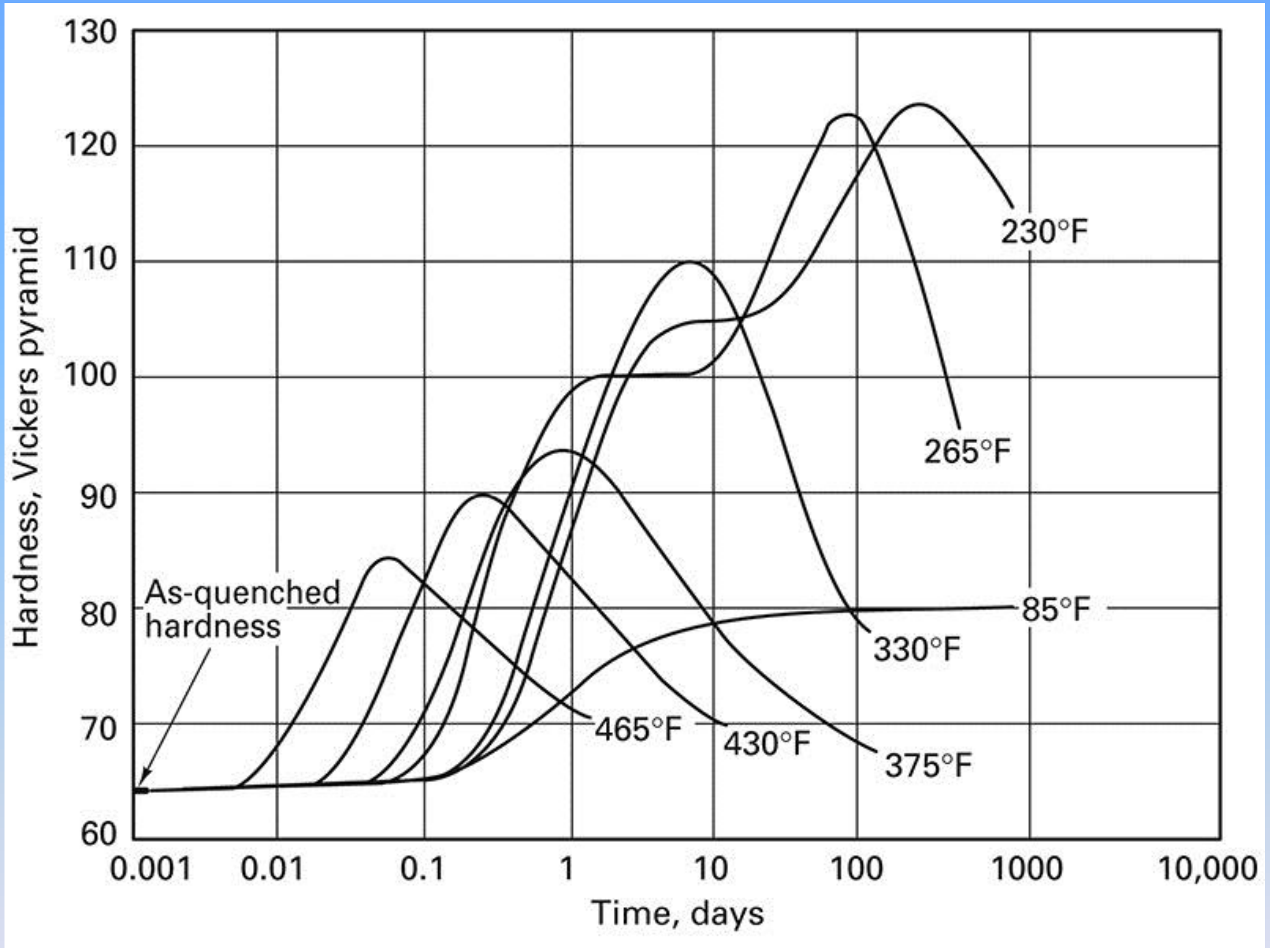


Figure 5-6 Aging curves for the Al-4%Cu alloy at various temperatures showing peak strengths and times of attainment. (Adapted from Journal of the Institute of Metals, Vol. 79, p. 321, 1951.)

6.5 Strengthening Heat Treatments for Steel

- Steel is the most common material to be heat treated
- Isothermal transformation (I-T) or time-temperature-transformation (T-T-T) diagrams are used to understand the process
- Phase transformations are most rapid at an intermediate temperature
  - C-structure represents this phenomenon

6.5 T-T-T Diagram

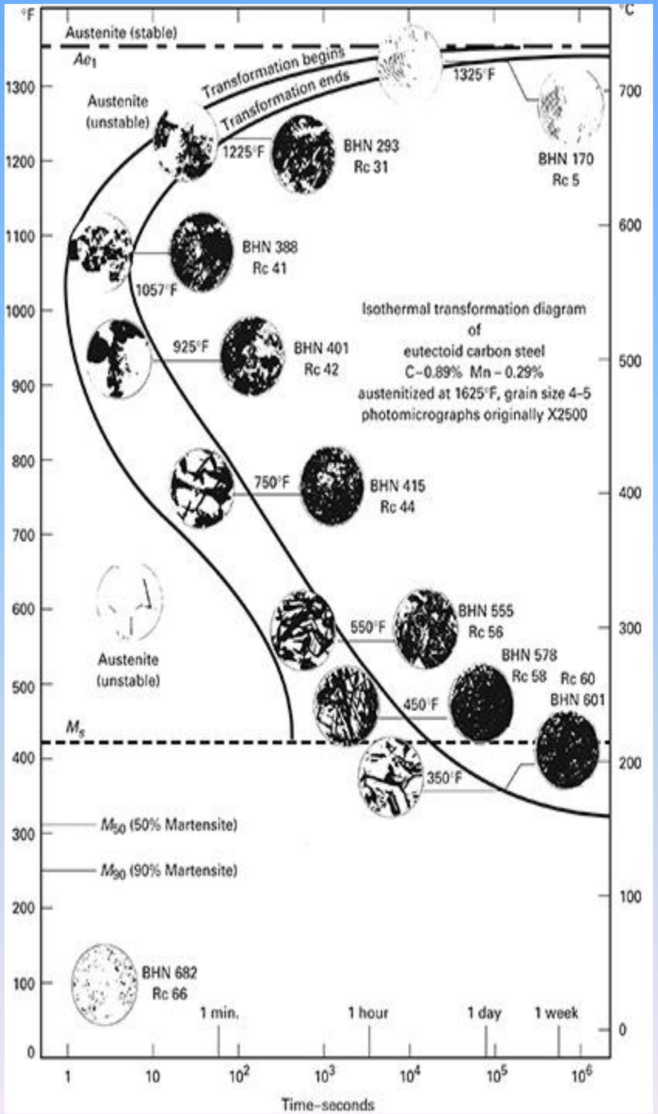
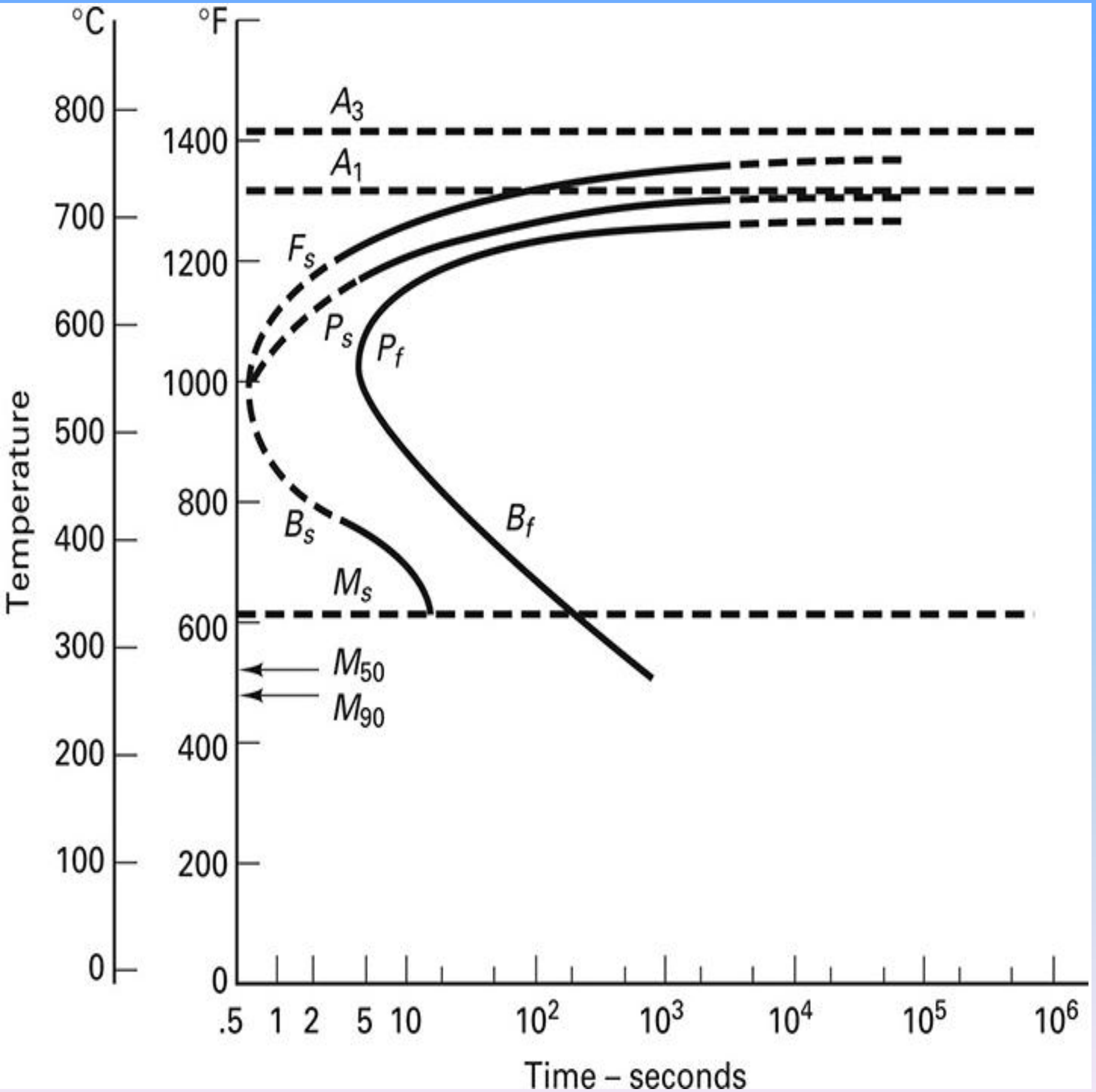


Figure 5-7 Isothermal transformation diagram (T-T-T diagram) for eutectoid composition steel. Structures resulting from transformation at various temperatures are shown as insets. (Courtesy of United States Steel Corp., Pittsburgh, PA.)

6.5 CCT of Steel



6.5 Tempering

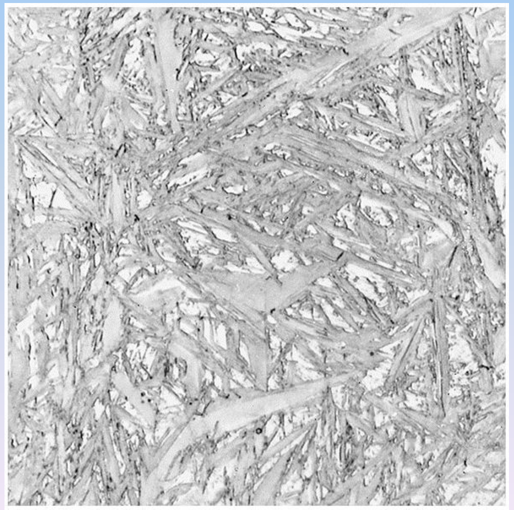
- This is the most common heat treatment
- Involves reheating quenched steel to a temperature bellow the eutectoid temperature then cooling.
- The elevated temperature allows very small amounts of spheroidite to form
- This restores ductility, but reduces hardness.

6.5 Martensite Transformation

- Carbon steel with at least 0.4 wt% C is heated to normalizing temperatures and then rapidly cooled (quenched) in water, brine, or oil to the critical temperature.
- The critical temperature is dependent on the carbon content, but as a general rule is lower as the carbon content increases.
- The steel possesses a super-saturated carbon content.
- The steel is extremely hard but brittle, usually too brittle for practical purposes.
- The internal stresses cause stress cracks on the surface.

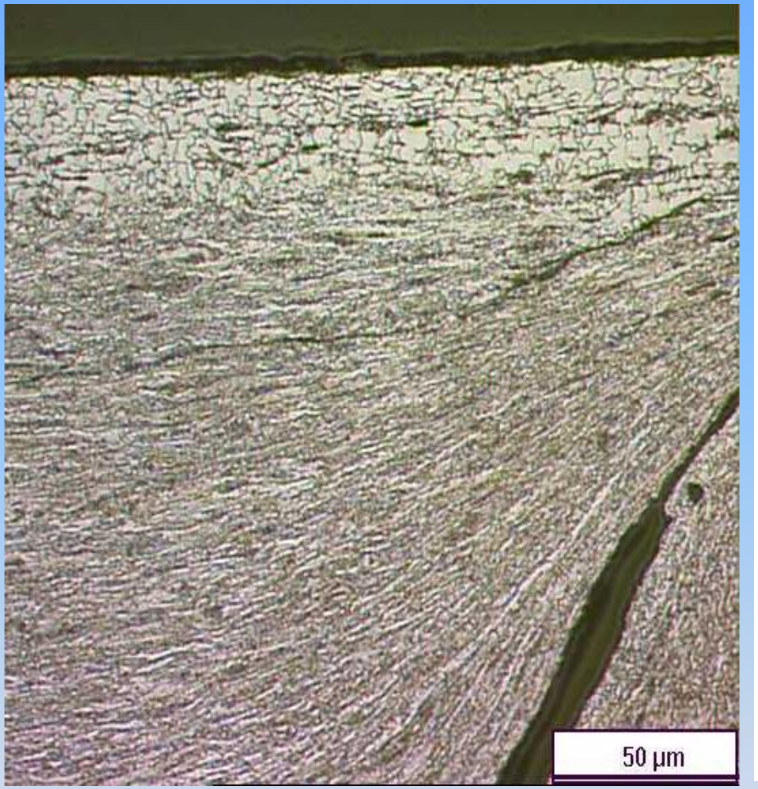
6.5 Tempering of Martensite

- Initially after it has been quenched, martensite lacks the toughness and ductility for engineering applications.
- Tempering is a subsequent heating to give the steel necessary ductility and fracture toughness



Photomicrograph of martensite 1000X

6.5 Recrystalized Oxidized Fragment



- Left: heavily deformed and recrystalized regions, 500X
- Right: recovered oxidized fragment (t=390 deg C)

6.5 Maraging Steels

- **Maraging steels** (a portmanteau of martensitic and aging) are iron alloys which are known for possessing superior strength and toughness without losing malleability.
- A special class of low carbon ultra-high strength steels which derive their strength not from carbon, but from precipitation of inter-metallic compounds.
- The principal alloying element is 15 to 25% nickel.[1]
- Secondary alloying elements are added to produce intermetallic precipitates, which include cobalt, molybdenum, and titanium.[1]
- Original development was carried out on 20 and 25% Ni steels to which small additions of Al, Ti, and Nb were made.

Additional Heat Treatments

- Process anneal
  - Recrystallization is induced after a material has been cold worked to reduce strain hardening effects
  - Induces a change in size, shape, and distribution
- Stress-relief anneal
  - Reduces residual stresses in casting, welded assemblies, and cold-formed products
  - Materials are heated and then slow cooled
- Spheroidization
  - Objective is to produce a structure in which all of the cementite is in the form of small spheroids or globules dispersed throughout a ferrite matrix

Martensite

- If excess carbon becomes trapped in the microstructure, it becomes a distorted BCC structure.
- This new structure is known as martensite.
- The hardness and strength of steel with martensitic structure are strong functions of the carbon content.
- The amount of martensite that forms is not a function of time, but the temperature during quenching.

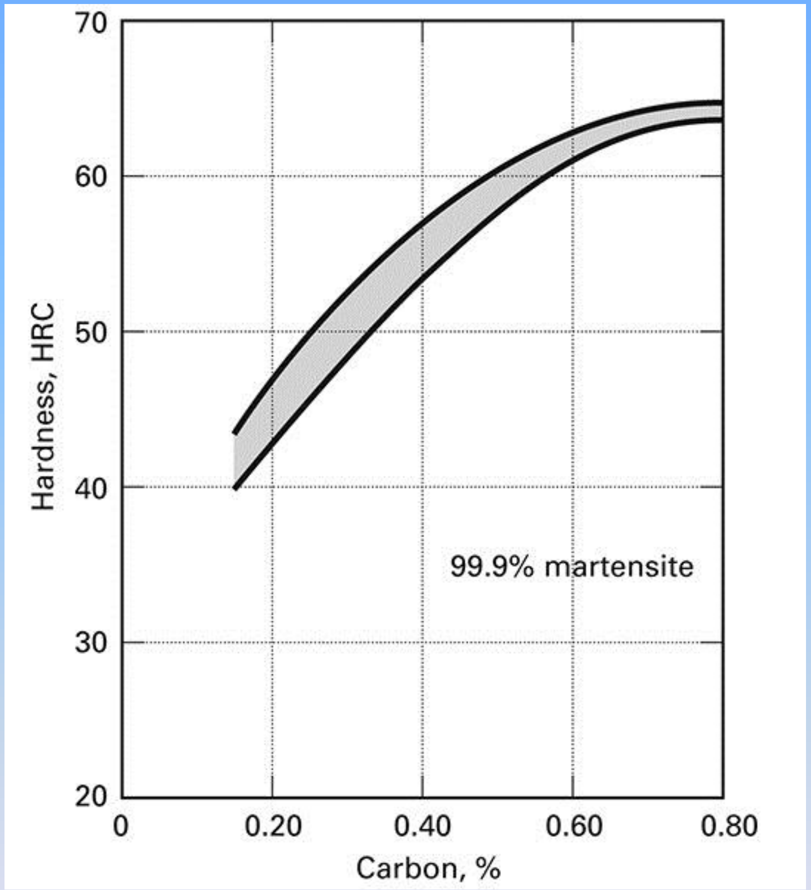


Figure 5-9 Effect of carbon on the hardness of martensite.

Tempering of Martensite

- Initially after it has been quenched, martensite lacks the toughness and ductility for engineering applications.
- Tempering is a subsequent heating to give the steel necessary ductility and fracture toughness

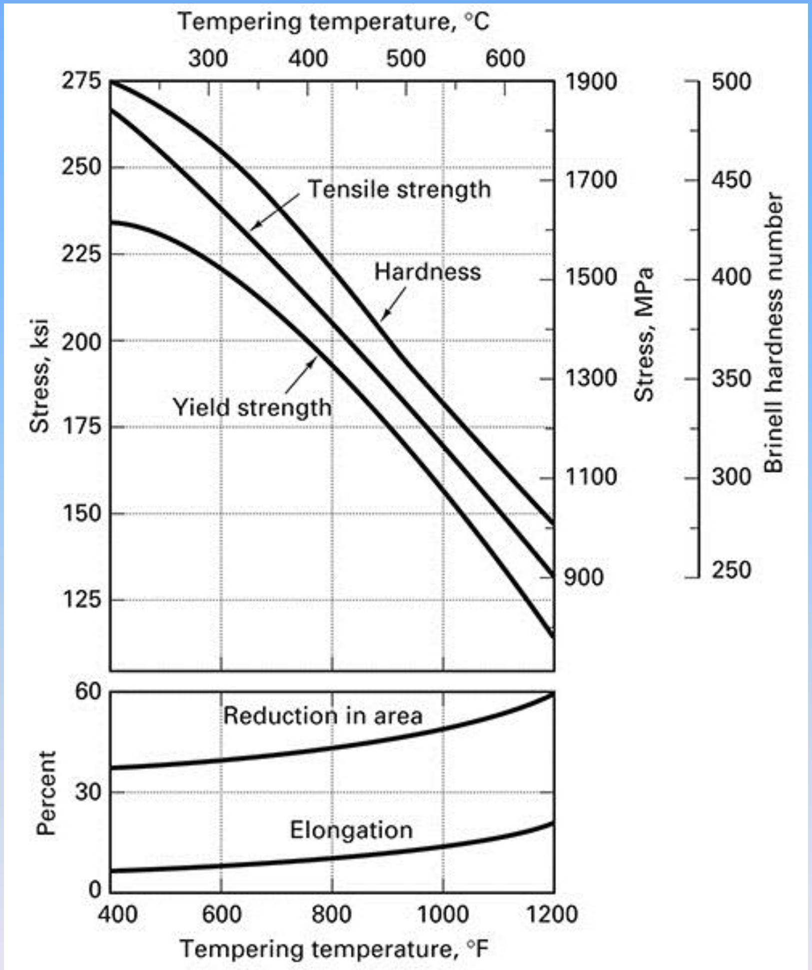
Tempering of Martensite

TABLE 5-1 Comparison of Age Hardening with the Quench-and-Temper Process

Heat Treatment	Step 1	Step 2	Step 3
Age hardening	*Solution treatment.* Heat into the stable single-phase region (above the solvus) and hold to form a uniform-chemistry single-phase solid solution.	*Quench.* Rapid cool to form a nonequilibrium supersaturated single-phase solid solution (crystal structure remains unchanged, material is soft and ductile).	*Age.* A controlled reheat in the stable two-phase region (below the solvus). The material moves toward the formation of the stable two-phase structure, becoming stronger and harder. The properties can be "frozen in" by dropping the temperature to stop further diffusion.
Quench and temper for steel	*Austenitize.* Heat into the stable single-phase region (above the A_3 or A_{cm}) and hold to form a uniform-chemistry single-phase solid solution (austenite).	*Quench.* Rapid cool to form a nonequilibrium supersaturated single-phase solid solution (crystal structure changes to body-centered martensite, which is hard but brittle).	*Temper.* A controlled reheat in the stable two-phase region (below the A_1). The material moves toward the formation of the stable two-phase structure, becoming weaker but tougher. The properties can be "frozen in" by dropping the temperature to stop further diffusion.

Properties of Processed Steel

Figure 5-13 Properties of an AISI 4140 steel that has been austenitized, oil-quenched, and tempered at various temperatures. (Adapted from Engineering Properties of Steel, ASM International, Materials Park, OH., 1982.)



Continuous Cooling Transformations

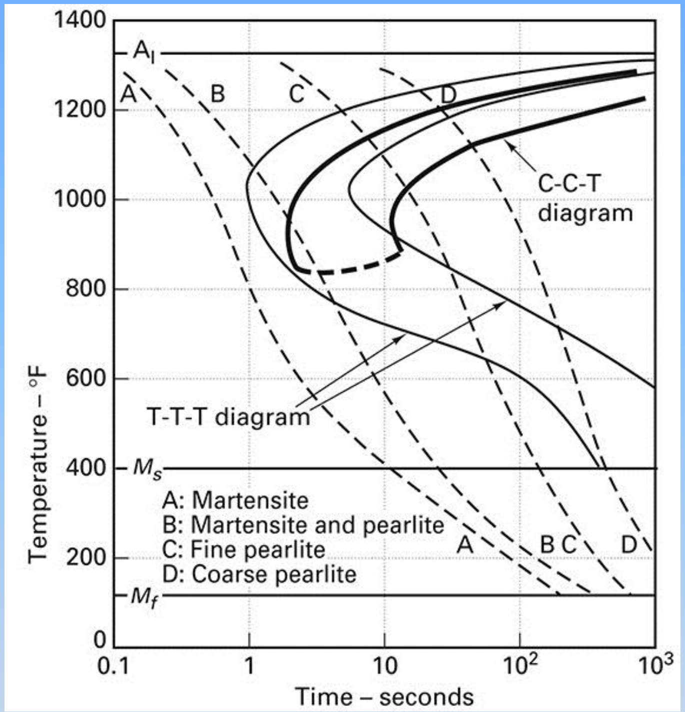


Figure 5-14 C-C-T diagram for a eutectoid composition steel (bold), with several superimposed cooling curves and the resultant structures. The lighter curves are the T-T-T transitions for the same steel. (Courtesy of United States Steel Corp., Pittsburgh, PA.)

- TTT curves assume that the properties of instantaneous heating followed by constant temperature transformation match reality
- Continuous cooling transformations (CCT) diagrams show a more accurate picture of the transformations

Jominy Test for Hardenability

- material + cooling rate→structure→properties
- A heated material is quenched from one end
- Standards for Jominy test
  - Quench medium
  - Internal nozzle diameter
  - Water pressure
- All cooling is along the axis of the bar
- After the bar is cooled, Rockwell hardness readings are taken (i.e. strength)

Jominy Hardness Test

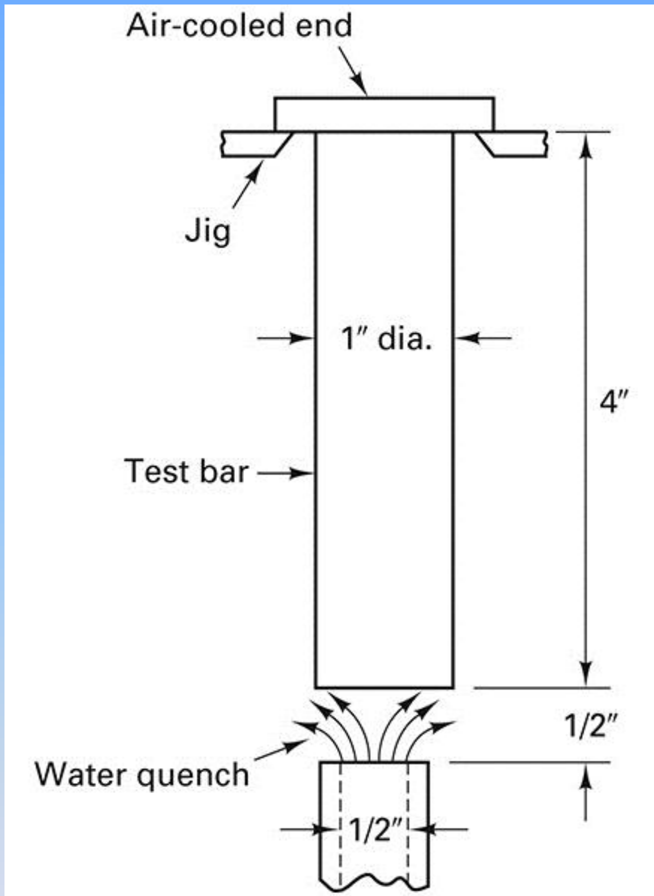


Figure 5-15 Schematic diagram of the Jominy hardenability test.

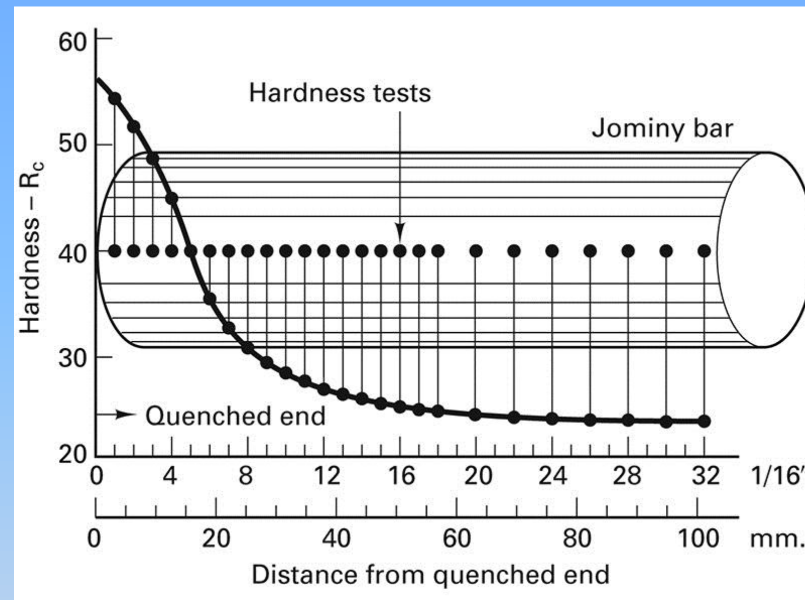


Figure 5-16 Typical hardness distribution along a Jominy test specimen.

Hardenability Considerations

- Hardness is a material property that is related to strength
  - Strong function of the carbon content and microstructure
- Hardenability measures the ability of a material to be fully hardened under normal hardening cycles
  - Related to the amounts and types of alloying elements
- Primary reason to add an alloying element is to increase hardenability
- The greater a material's hardenability, the easier it is for a material to be slow cooled
  - Slow cooling reduces the probability of quench-cracking

Quench Media

- Quenchants are the medium in which a material is quenched
  - Selected to provide necessary cooling rates
- Stages of quenching
  - Formation of the vapor jacket
    - Vapor jacket is the thin gaseous layer between the metal and the liquid during cooling
  - Nucleate boiling phase
    - Produces rapid rates of cooling down to the boiling point of the quenchant
  - Conduction and convection
    - Slower cooling from the boiling point to room temperature

Quenching Considerations

- Water is an effective quenching medium because of its high heat of vaporization and relatively high boiling point
  - The quenchant should be agitated due to the tendency of bubbles to form soft spots on the metal
  - A negative consequence is that it may oxidize the material
- Brine is similar to water as a quenchant medium
  - Rapid cooling occurs because the salt nucleates bubbles
  - Corrosion problems may exist

Quenching Considerations

- Oil is utilized if slower quenching rates are desired
  - Oil may cause water contamination, smoke, fumes, etc.
  - More expensive than water or brine quenchants
- Water based polymer quenchants have properties between oil and water and brine
- Molten salt baths may be used for even slower cooling rates
- High pressure quenching uses a stream of flowing gas to extract heat

Design Concerns, Residual Stresses, Distortion, and Cracking

- Product and design and material selection play an important role in proper heat treatment of parts
- Residual stresses are stresses that exist in a part independent of an applied stress
- Most parts being heat treated experience nonuniform temperatures during cooling or quenching

Model of Cooling

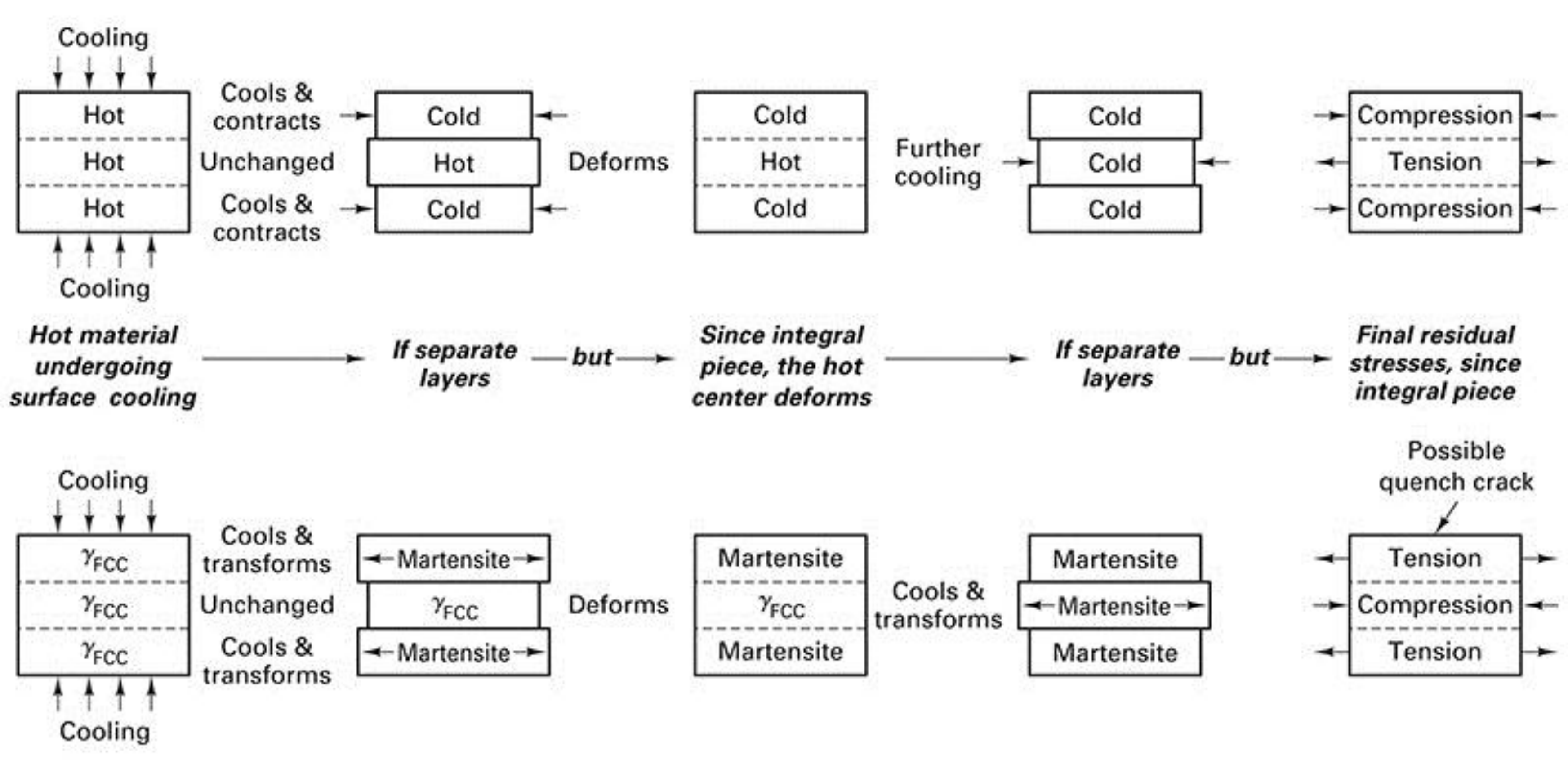


Figure 5-19 Three-layer model of a plate undergoing cooling. The upper sequence depicts a material such as aluminum that contracts upon cooling while the bottom sequence depicts steel, which expands during the cooling-induced phase transformation.

Design Considerations

- Ways to prevent quench cracking and residual stresses
  - More uniform cross-sectional area
  - Generous fillets
  - Radiused corners
  - Smooth transitions
  - Adding additional holes
- Residual stresses can accelerate corrosion problems

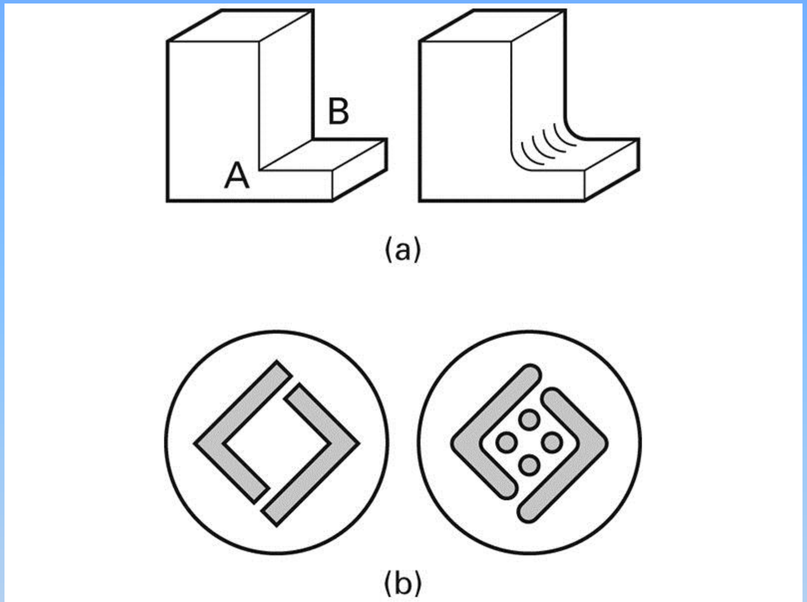


Figure 5-20 a) Shape containing nonuniform sections and a sharp interior corner that may crack during quenching. This is improved by using a large radius to join the sections. b) Original design containing sharp corner holes, which can be further modified to produce more uniform sections.

Techniques to Reduce Cracking and Distortion

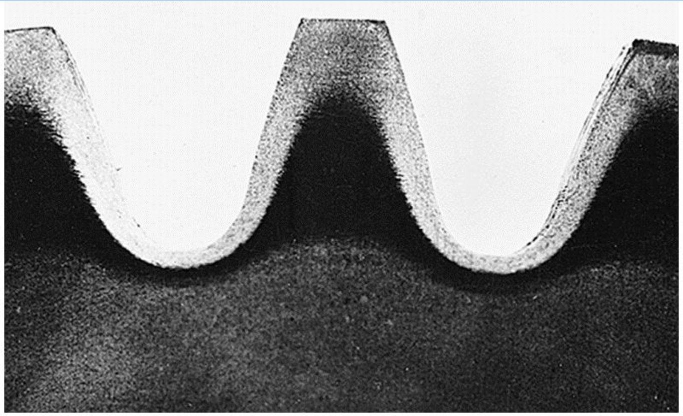
- Rapid cools may be used to prevent pearlite transformation
  - Instead of quenching in a liquid medium, the metal is quenched in a hot oil or molten salt bath to allow the entire piece to return to a nearly uniform temperature
  - If the metal is held at this temperature for enough time, the austenite will turn to bainite
    - Process is known as austempering
  - If the metal is brought to a uniform temperature and then slow cooled through martensite transformation, the process is known as martempering

Ausforming

- Commonly confused with austempering
- Material is heated to form austenite and then quenched to a temperature between pearlite and bainite
- Increased ductility
- Finer grain size
- Some degree of strain hardening

6.6 Surface Hardening of Steel

- Methods to produce properties that vary throughout the material
  - Selective heating of the surface
  - Altered surface chemistry
  - Deposition of an additional surface layer
  - Section of gear teeth showing induction hardened surfaces (Figure)



Selective Heating Techniques

- Surface properties are established by surface treatments
  - Flame hardening
    - Uses an oxy-acetylene flame to raise the surface temperature to reform austenite
    - Surface is then water quenched to form martensite
    - Tempered to a desired hardness
  - Induction hardening
    - Steel part is placed inside a conductor coil and alternating current is used to change the surface of the steel
    - Rate and depth of heating can be controlled
    - Ideal for round bars and cylindrical parts

Selective Heating Techniques

- Laser beam hardening
  - Produces hardened surfaces
  - Absorptive coatings (zinc or manganese phosphate) are applied to the steel to increase efficiency
  - Beam size, beam intensity, and scanning speed are adjustable to affect the depth of heating
- Electron beam hardening
  - Similar to laser beam hardening
  - Heat source is a beam of high-energy electrons

Techniques Involving Altered Surface Chemistry

- Carburizing is the diffusion of carbon into FCC, austenite steel at elevated temperatures
  - In gas carburizing, a hot gas containing carbon surround the part
  - In pack carburizing, the steel is surrounded by a solid that contains carbon
  - In liquid carburizing, the steel is placed in a molten bath with carbon

Techniques Involving Altered Surface Chemistry

- Nitriding hardens the surfaces by producing alloy nitrides in special steels that contain nitride-forming elements
  - Aluminum, chromium, molybdenum, vanadium
- Ionitriding is a plasma process that places parts in an evacuated furnace and treats them with direct current potential
  - Low pressure nitrogen is then introduced into the furnace and becomes ionized
- Ion carburizing is similar to ionitriding except that methane is introduced instead of nitrogen
- Carbonitriding is where both nitrogen and carbon are introduced

6.7 Furnaces

- Furnace types
  - Parts remain stationary in batch furnaces
  - Continuous furnaces move the components through heat treating processes that are compatible with other manufacturing processes
    - Box furnaces are horizontal batch furnaces
    - Car-bottom-box furnaces are used for large and long workpieces
  - Bell furnaces place a “bell” over the workpiece to control heating and cooling
    - Elevator furnaces
  - Vertical pit furnaces prevent horizontal sagging or warping

Furnace Atmospheres

- Artificial gas atmospheres
  - Prevents scaling or tarnishing
- Fluidized-bed
  - Inert particles are heated and suspended in a stream of gas
- Salt bath furnaces
  - Salt is heated by passing a current between two electrodes placed in the batch
  - Lead pot is a bath where lead is used instead of salt
- Electrical induction heating

6.8 Heat Treatment and Energy

- Heat treatments can consume significant amounts of energy
  - High temperatures
  - Long heating times
- Manufacture of more durable products eliminates frequent replacements
- Higher strengths may allow for less material
- Industry is trying to reduce energy consumption, processing times, and emissions

Summary

- Heat treatments are used to control material properties
- Mechanical properties may be changed by changing the microstructure of the material
- T-T-T and C-C-T curves are used to understand the heat treating processes
- Selective heating may be used to only change properties of the material at certain points on the part