Chapter Outline: Thermal Processing of Metal Alloys

In this chapter we will learn more on how different thermal processing techniques can be used to control microstructure of metal alloys and their mechanical properties

- Annealing, Stress Relief
- More on Heat Treatment of Steels
- Precipitation Hardening

Annealing

Annealing - heat treatment in which a material is taken to an elevated temperature, kept there for some time and then cooled.

Stages of annealing:

- Heating to required temperature
- Holding ("soaking") at constant temperature
- Cooling

The time at the high temperature (soaking time) is long enough to allow the desired transformation to occur.

Cooling is done slowly to avoid warping/cracking of due to the thermal gradients and thermo-elastic stresses within the or even cracking the metal piece.

Purposes of annealing:

- Relieve internal stresses
- Increase ductility, toughness, softness
- Produce specific microstructure

Examples of heat treatment

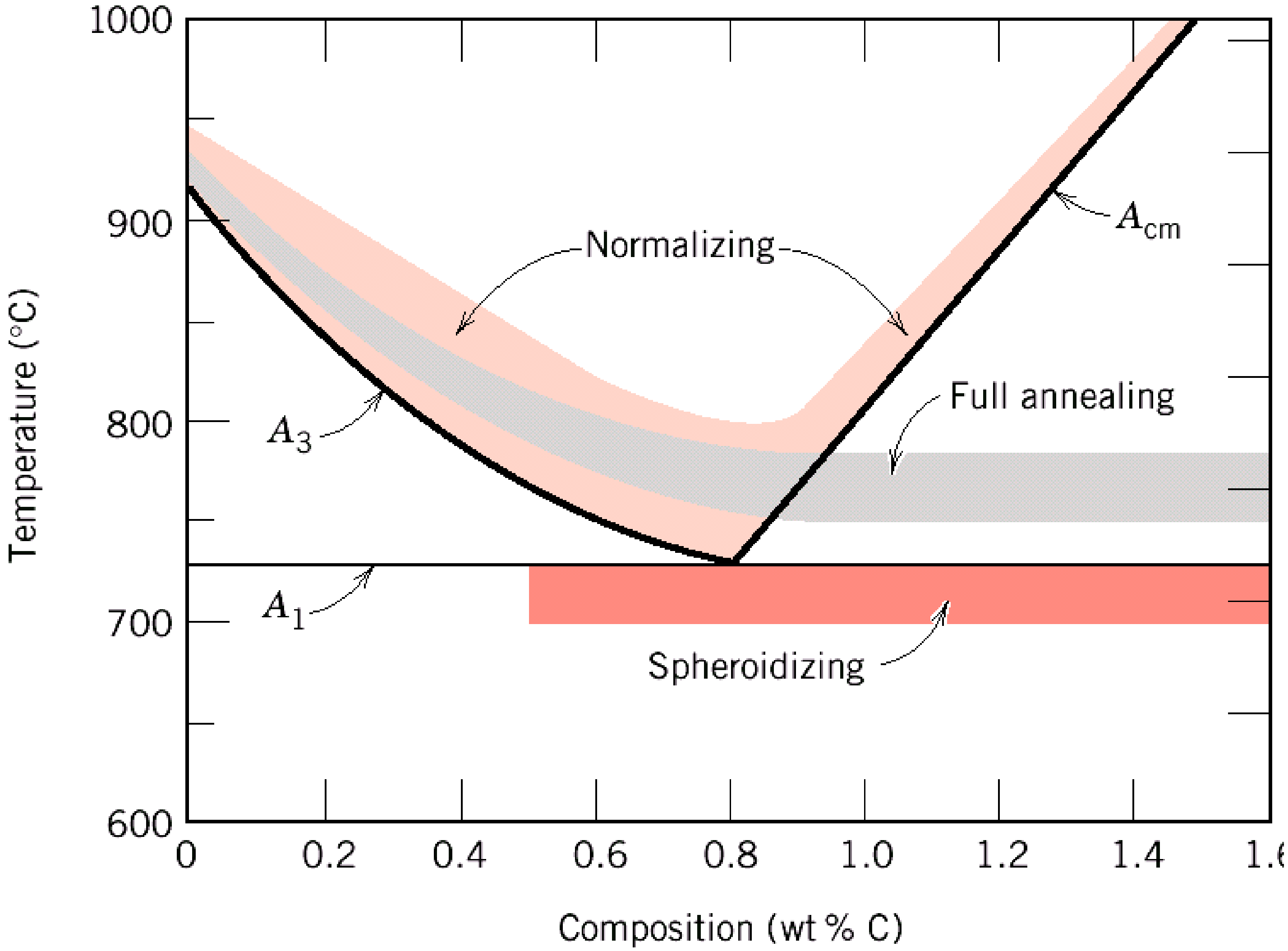
Process Annealing - used to revert effects of work-hardening (by recovery and recrystallization) and to increase ductility. Heating is usually limited to avoid excessive grain growth and oxidation.

Stress Relief Annealing – used to eliminate/minimize stresses arising from

- o Plastic deformation during machining
- o Nonuniform cooling
- o Phase transformations between phases with different densities

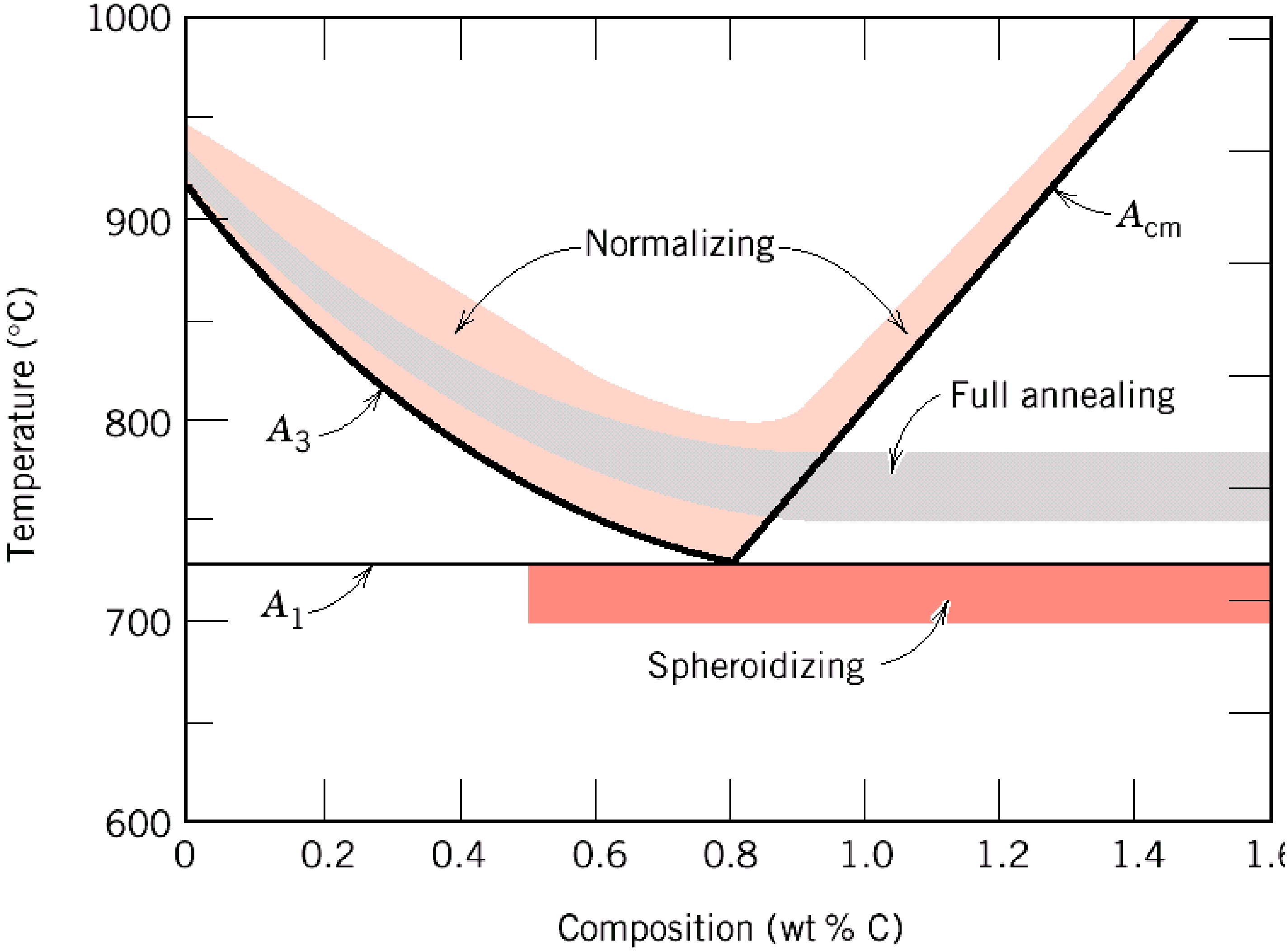
Stress relief annealing allows these stresses to relax. Annealing temperatures are relatively low so that useful effects of cold working are not eliminated.

Annealing of Fe-C Alloys (I)



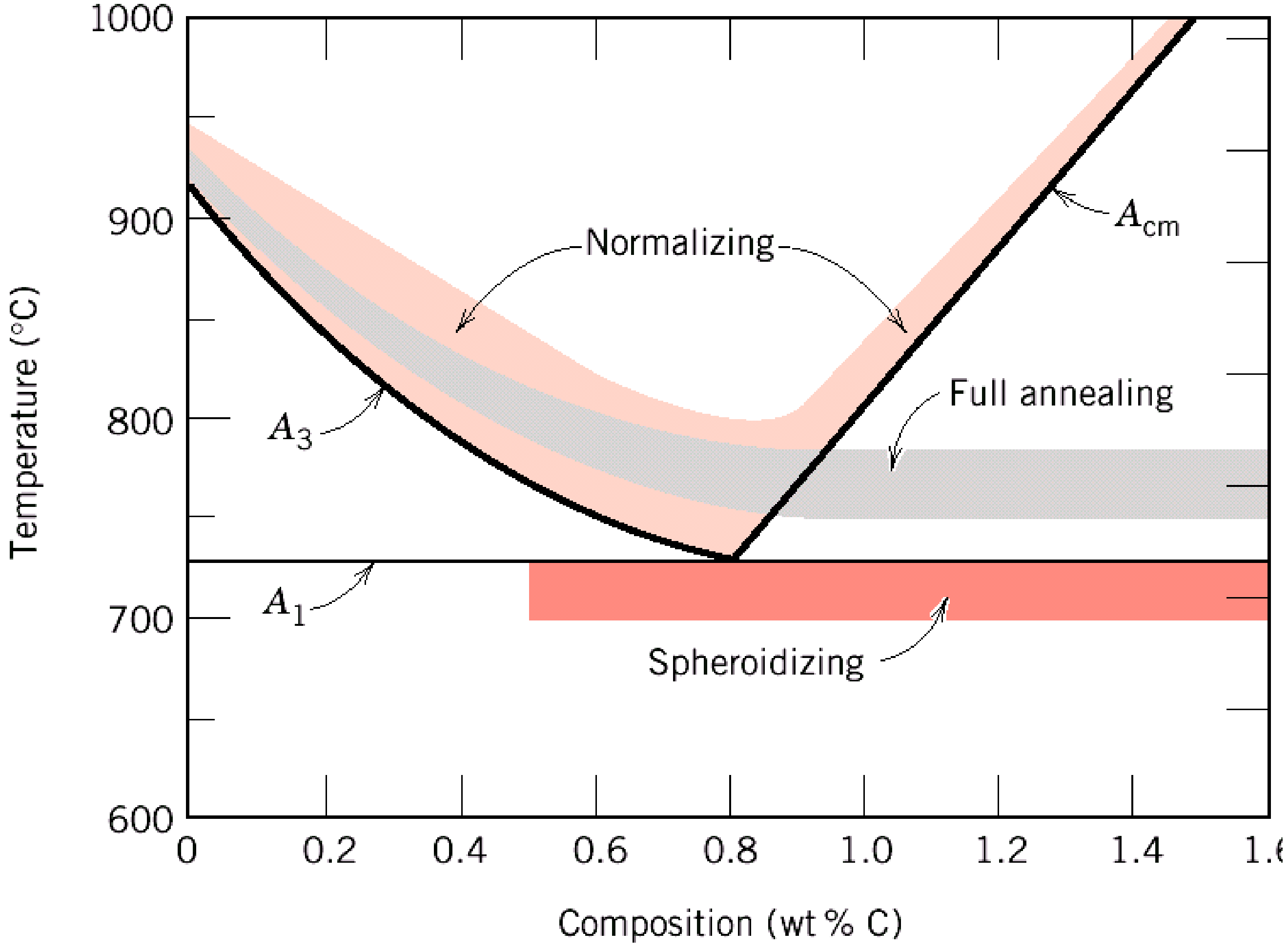
- **Lower critical temperature** A_1 below which austenite does not exist
- **Upper critical temperature** lines, A_3 and A_{cm} above which all material is austenite

Annealing of Fe-C Alloys (II)



Normalizing: an annealing heat treatment just above the upper critical temperature to reduce grain sizes (of pearlite and proeutectoid phase) and make more uniform size distributions. After complete transformation to austenite (austenitizing) the treatment is completed by cooling to the required microstructure.

Annealing of Fe-C Alloys (III)



Full annealing: austenizing and slow cooling (several hours). Produces coarse pearlite (and possible proeutectoid phase) that is relatively soft and ductile. Is used to soften pieces which have been hardened by plastic deformation, and which need to undergo subsequent machining/forming.

Spheroidizing: prolonged heating just below the eutectoid temperature, which results in the soft spheroidite structure discussed in Sect. 10.5. This achieves maximum softness needed in subsequent forming operations.

Heat Treatment of Steels

Martensite has the strongest microstructure and can be made more ductile by tempering. Therefore **the optimum properties of quenched and tempered steel are realized if high content of martensite is produced.**

Problem: difficult to maintain same conditions throughout volume of steel during cooling: surface cools more quickly than interior, producing range of microstructures through volume. The martensitic content, and the hardness, will drop from a high value at the surface to a lower value in the interior of the piece.

Production of **uniform martensitic structure** depends on

- composition
- quenching conditions
- size + shape of specimen

Hardenability

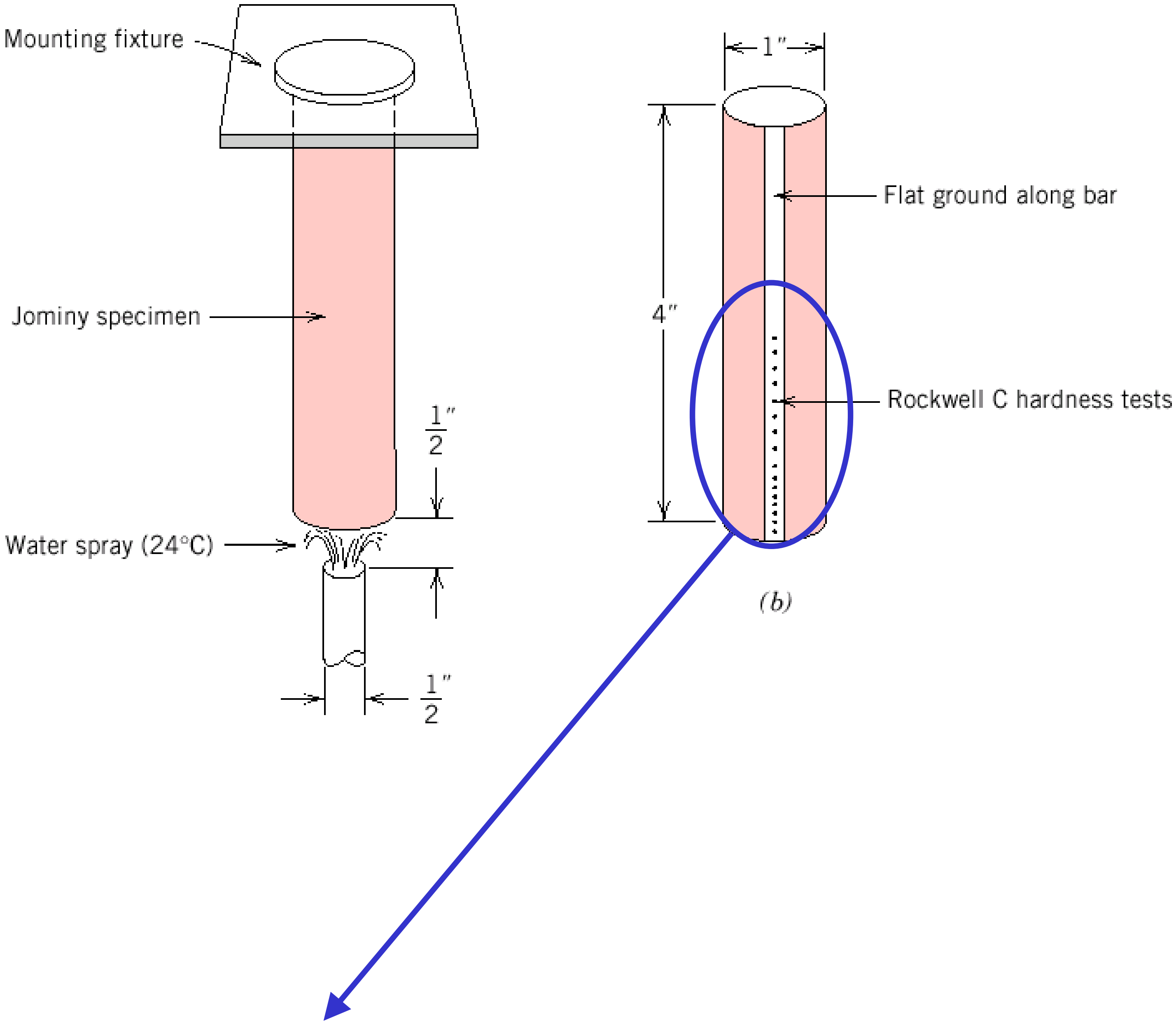
Hardenability is the ability of the Fe-C alloy to be hardened by forming martensite.

Hardenability is not "hardness". It is a qualitative measure of the rate at which hardness decreases with distance from the surface because of decreased martensite content.

High hardenability means the ability of the alloy to produce a high martensite content throughout the volume of specimen.

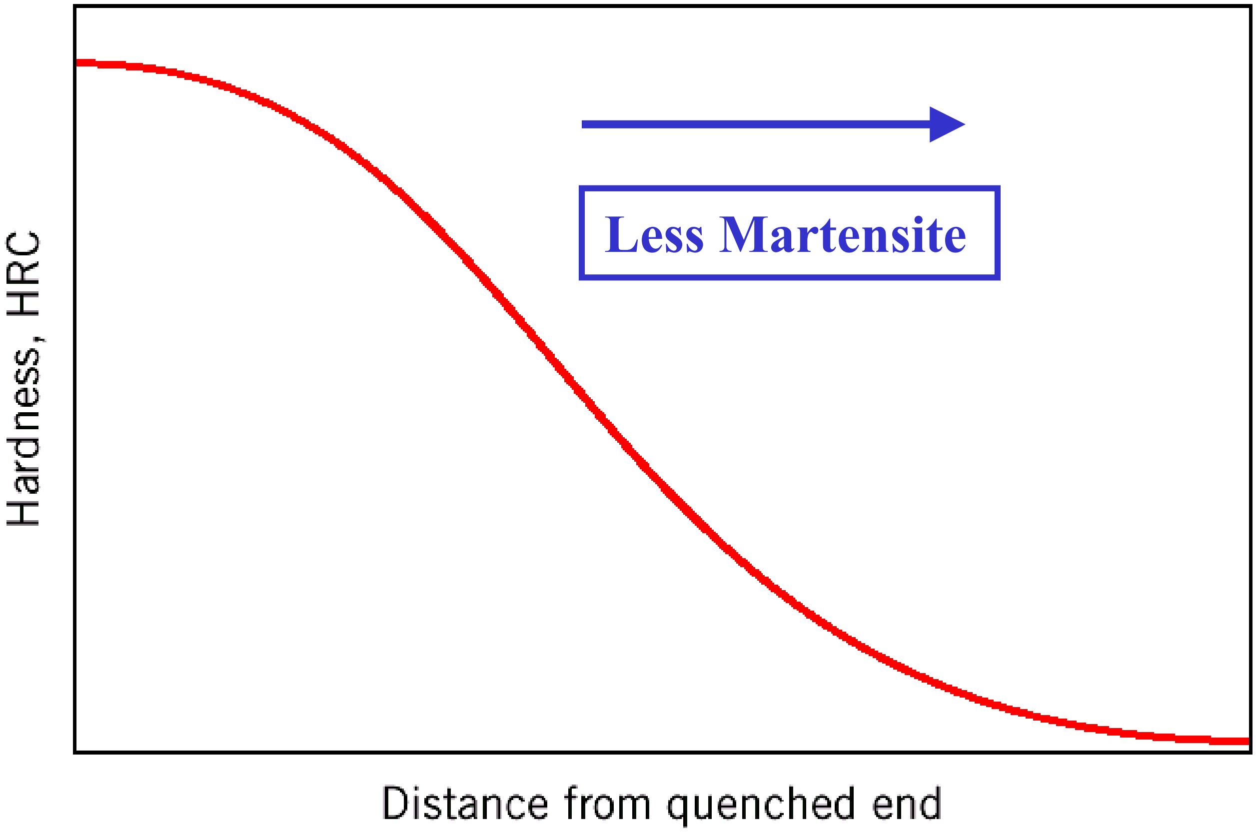
Hardenability is measured by the **Jominy end-quench test** performed for standard cylindrical specimen, standard austenitization conditions, and standard quenching conditions (jet of water at specific flow rate and temperature).

Jominy end-quench test of Hardenability



Hardenability curve is the dependence of hardness on distance from the quenched end.

Hardenability Curve



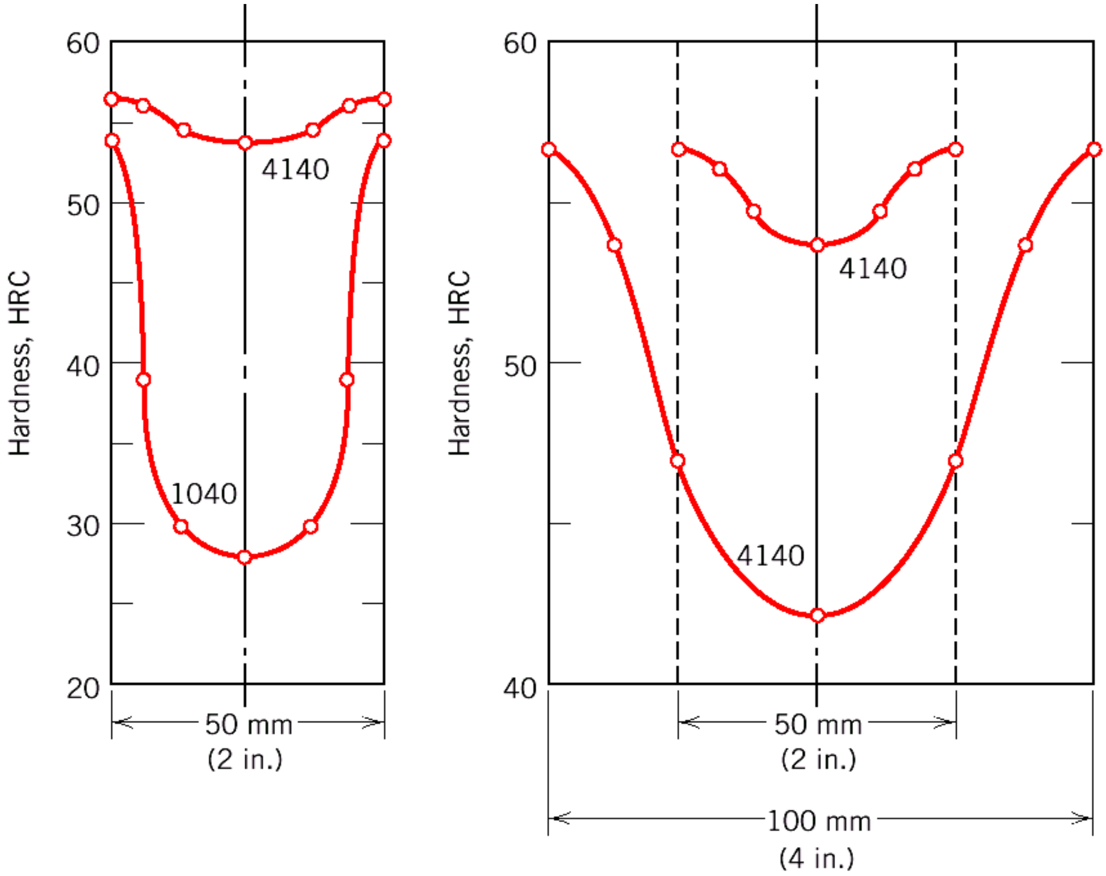
- Quenched end cools most rapidly and contains most martensite
- Cooling rate decreases with distance from quenched end: greater C diffusion, more pearlite/bainite, lower hardness
- High hardenability means that the hardness curve is relatively flat.

Influence of Quenching Medium, Specimen Size, and Geometry on Hardenability

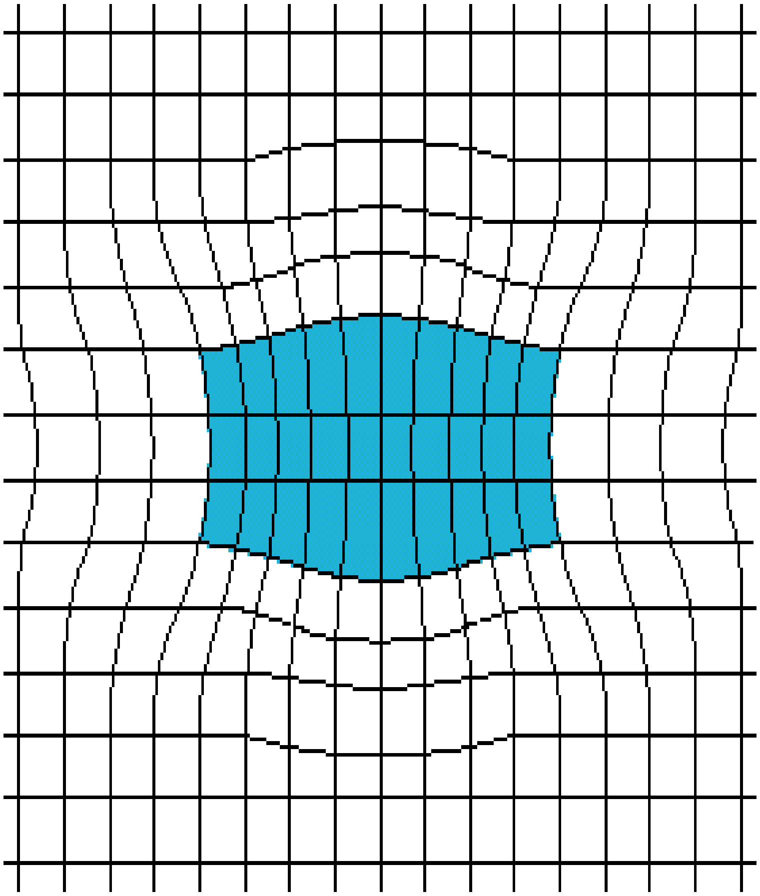
Quenching medium: Cooling is faster in water then oil, slow in air. Fast cooling brings the danger of warping and formation of cracks, since it is usually accompanied by large thermal gradients.

The shape and size of the piece: Cooling rate depends upon extraction of heat to specimen surface. Thus the greater the ration of surface area to volume, the deeper the hardening effect. Spheres cool slowest, irregularly shaped objects fastest.

Radial hardness profiles of cylindrical steel bars

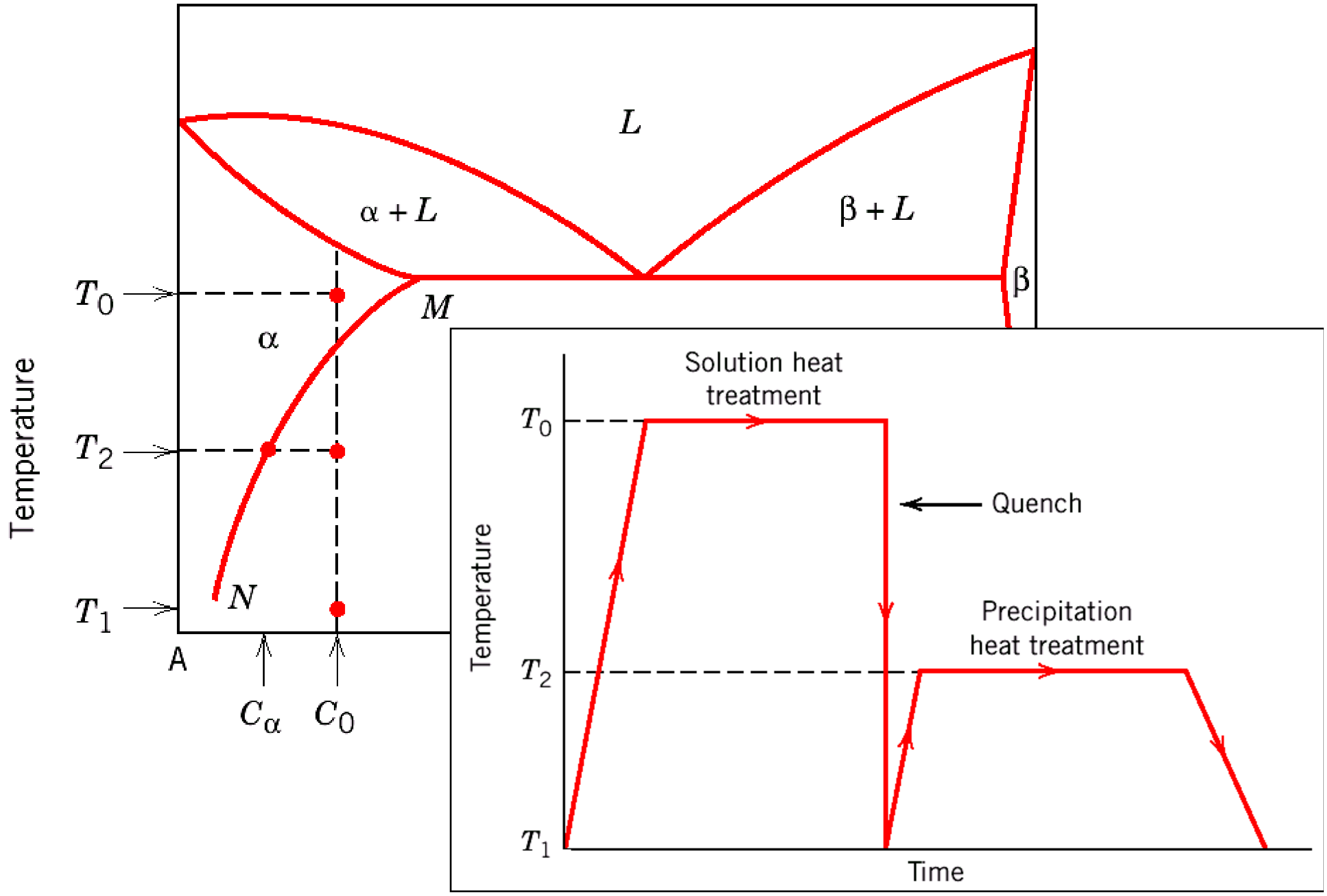


Precipitation Hardening



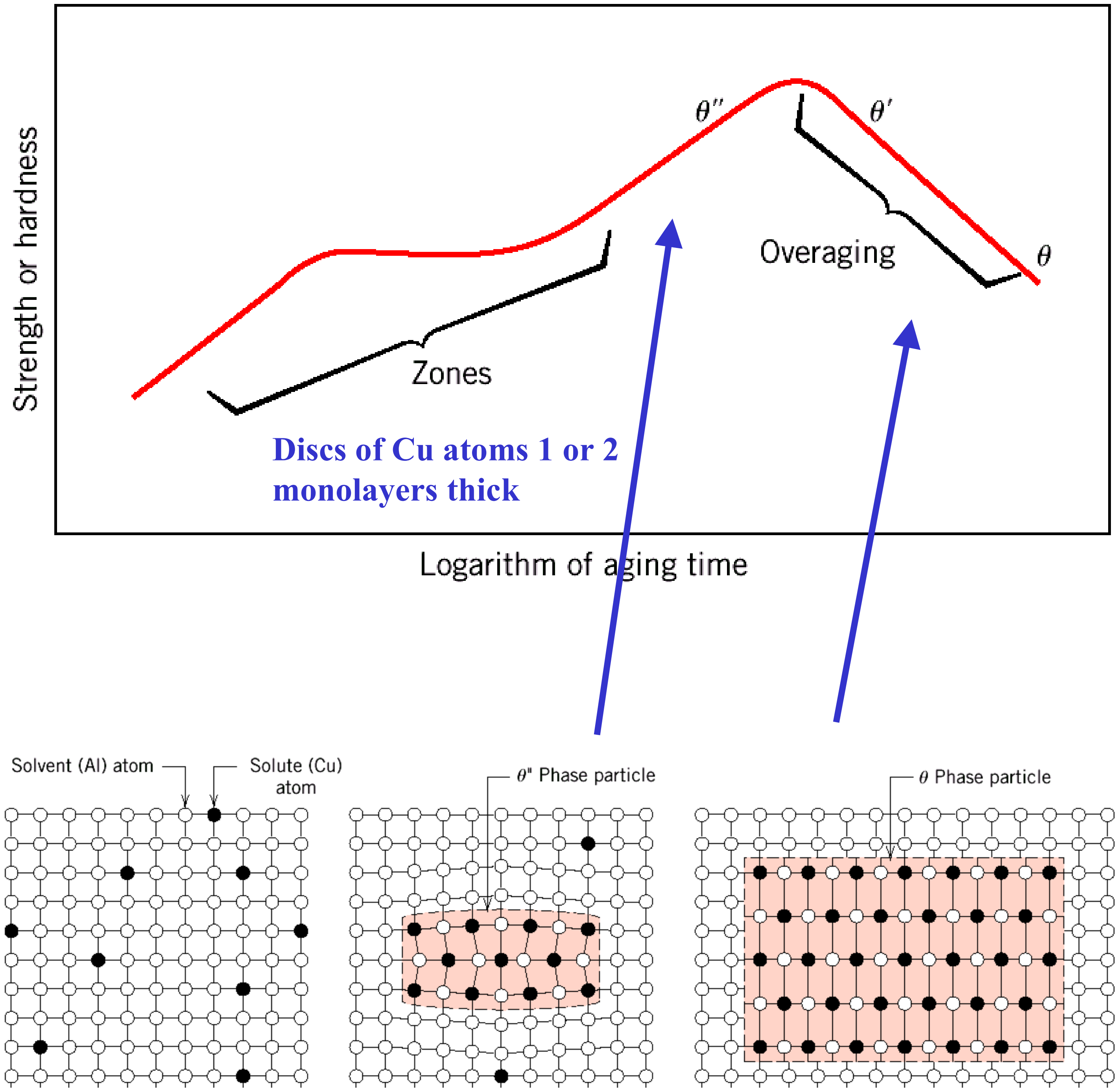
- Small inclusions of secondary phases strengthen material
- Lattice distortions around these secondary phases impede dislocation motion
- The precipitates form when the solubility limit is exceeded
- Precipitation hardening is also called **age hardening** because it involves the hardening of the material over a prolonged time.

Heat Treatment for Precipitation Hardening (I)



- **Solution heat treatment:** at T_o, all the solute atoms A are dissolved to form a single-phase (α) solution.
- **Rapid cooling** across the solvus line to exceed the solubility limit. This leads to a metastable supersaturated solid solution at T_1. Equilibrium structure is α+β, but limited diffusion does not allow β to form.
- **Precipitation heat treatment:** the supersaturated solution is heated to T_2 where diffusion is appreciable - β phase starts to form as finely dispersed particles: **ageing**.

Heat Treatment for Precipitation Hardening (II)

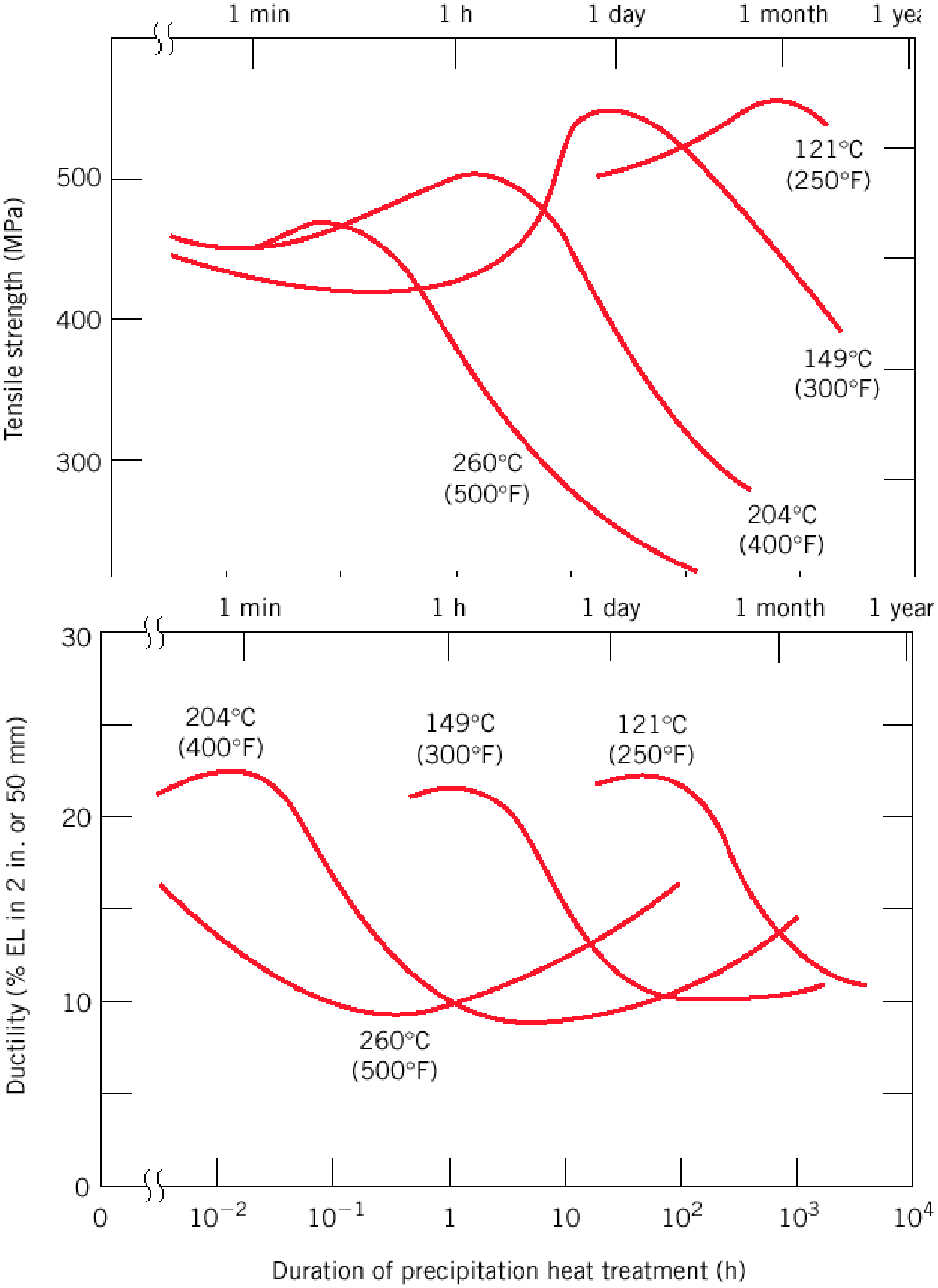


Discs of Cu atoms 1 or 2 monolayers thick

Lattice Distortions

No Lattice Distortions

Strength and ductility during precipitation hardening



Summary

Make sure you understand language and concepts:

- Annealing
- Austenitizing
- Full annealing
- Hardenability
- Jominy end-quench test
- Overaging
- Precipitation hardening
- Precipitation heat treatment
- Process annealing
- Solution heat treatment
- Spheroidizing
- Stress relief

Reading for next class:

Skip Chapter 12: Metal Alloys

Chapter 13: Structure and Properties of Ceramics

- Crystal Structures
- Silicate Ceramics
- Carbon
- Imperfections in Ceramics

Optional reading: 13.6 – 13.10

Chapter 14: Applications and Processing of Ceramics

- Short review of glass/ceramics applications and processing (14.1 - 14.7)

Optional reading: 14.8 – 14.18