



Student's Guide to Heat Treating

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Steel

What is Steel?



Steel is an alloy primarily composed of iron (Fe) and carbon (C), with other elements often added to modify its properties.

Iron atoms are arranged in a repeating crystal lattice at the atomic level.

Regions with the same crystal orientation form **grains** which make up the steel **microstructure**.

The microstructure, carbon content, alloying elements, and heat treatment strongly influence steel material properties.

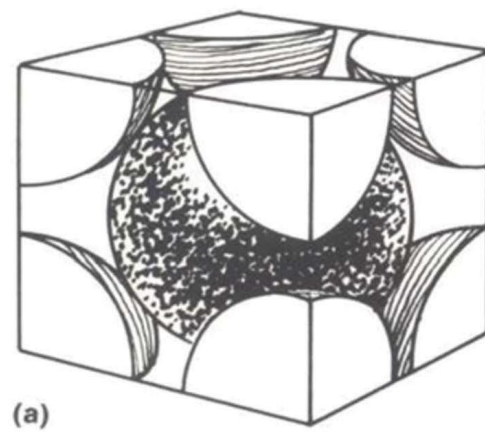
Steel is commonly classified by carbon content:

- Low-carbon steel
- Medium-carbon steel
- High-carbon steel

Crystal structure is the repeating, three-dimensional arrangement of atoms in a crystalline material.

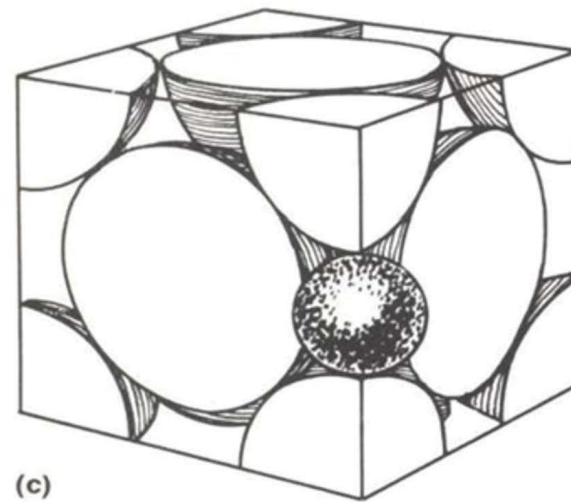
Crystal structure determines how atoms are arranged and influences material properties.

In steels, three major crystal structures:



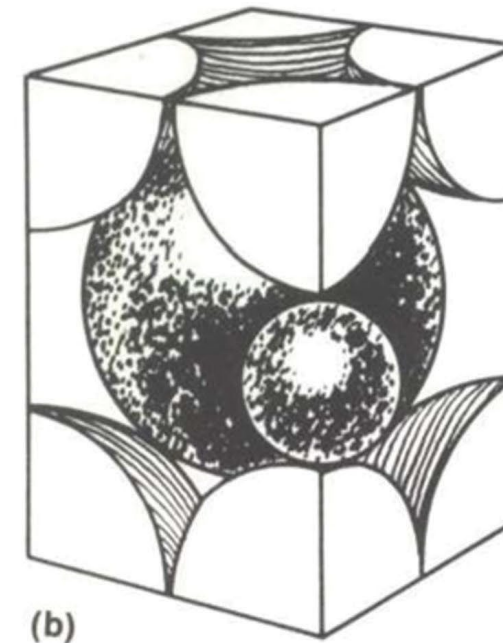
Body Centered Cubic (BCC)

- Fe atoms at corners + one in the center
- α -iron (ferrite) phase
- Low carbon solubility
- Relatively soft/ductile



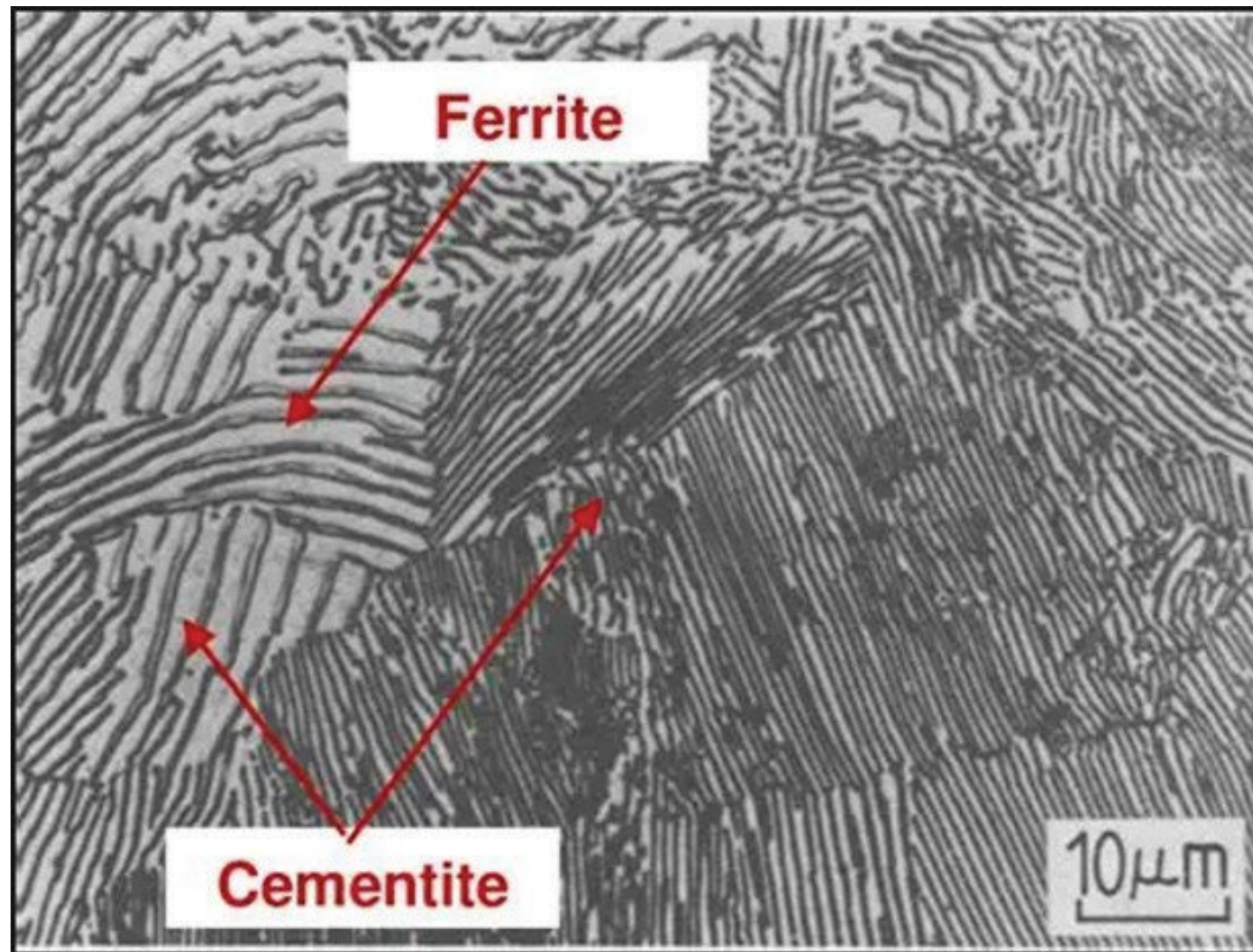
Face Centered Cubic (FCC)

- Fe atoms at corners + centers of faces
- Gamma-iron (austenite) phase
- Higher carbon solubility
- Stable at higher temperatures



Body Centered Tetragonal (BCT)

- Distorted BCC lattice structure due to carbon trapped in the interstitial sites
- Martensite phase formed by rapid quenching from austenite
- Very hard/strong



Pearlite microstructure showing characteristic fine lamellar arrangement of ferrite and cementite phases

What is a Phase?

-A physically or chemically distinct, homogeneous portion of a material with a particular structure and composition.

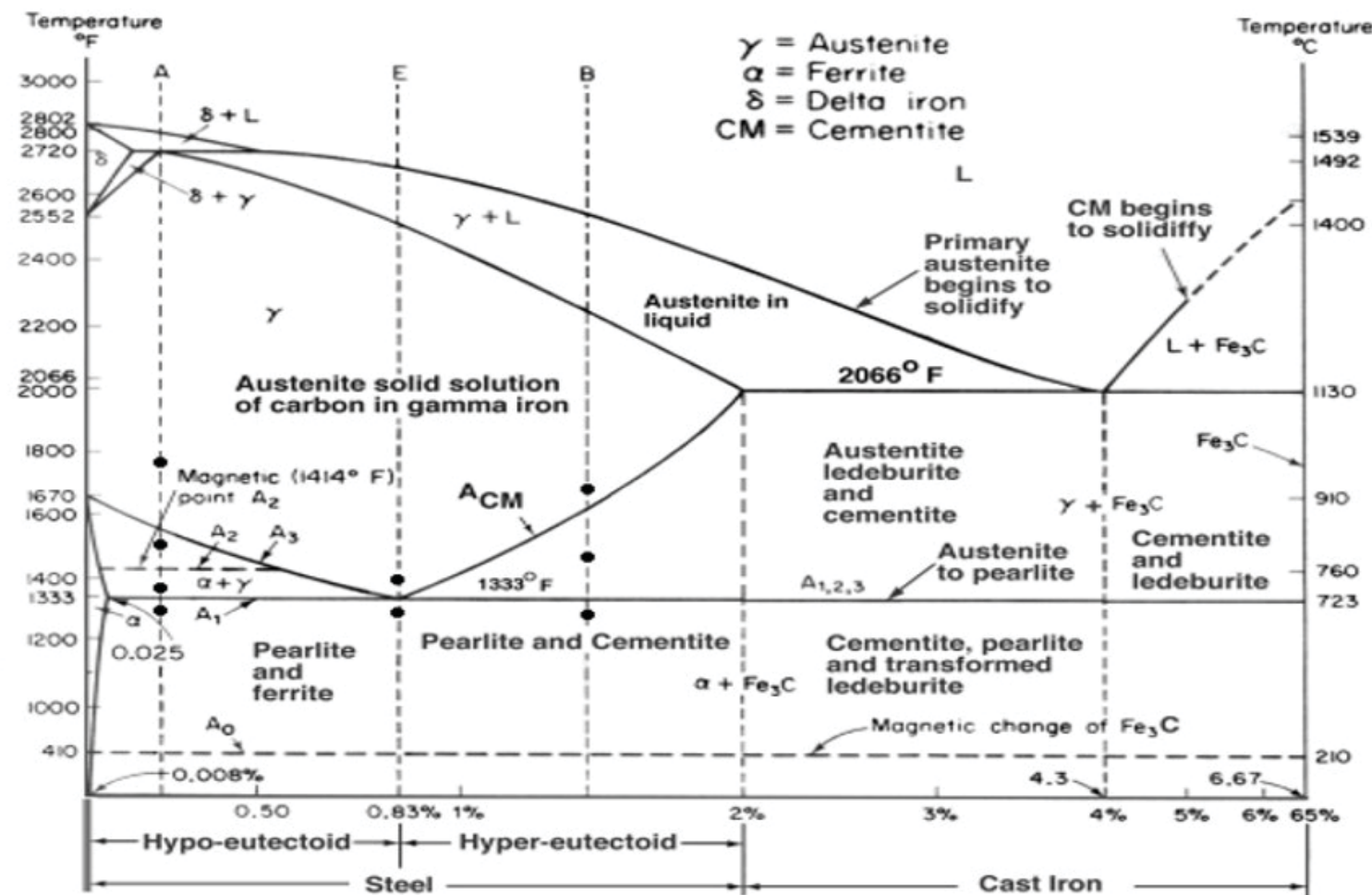
Phases: Ferrite (α), Austenite (γ), Cementite (Fe_3C)

A phase transformation is the change from one phase or microstructure state and occurs during heat treating.

What is a Microstructure?

- The arrangement of phases in steels.
- Different arrangement of phases can produce different microstructures.

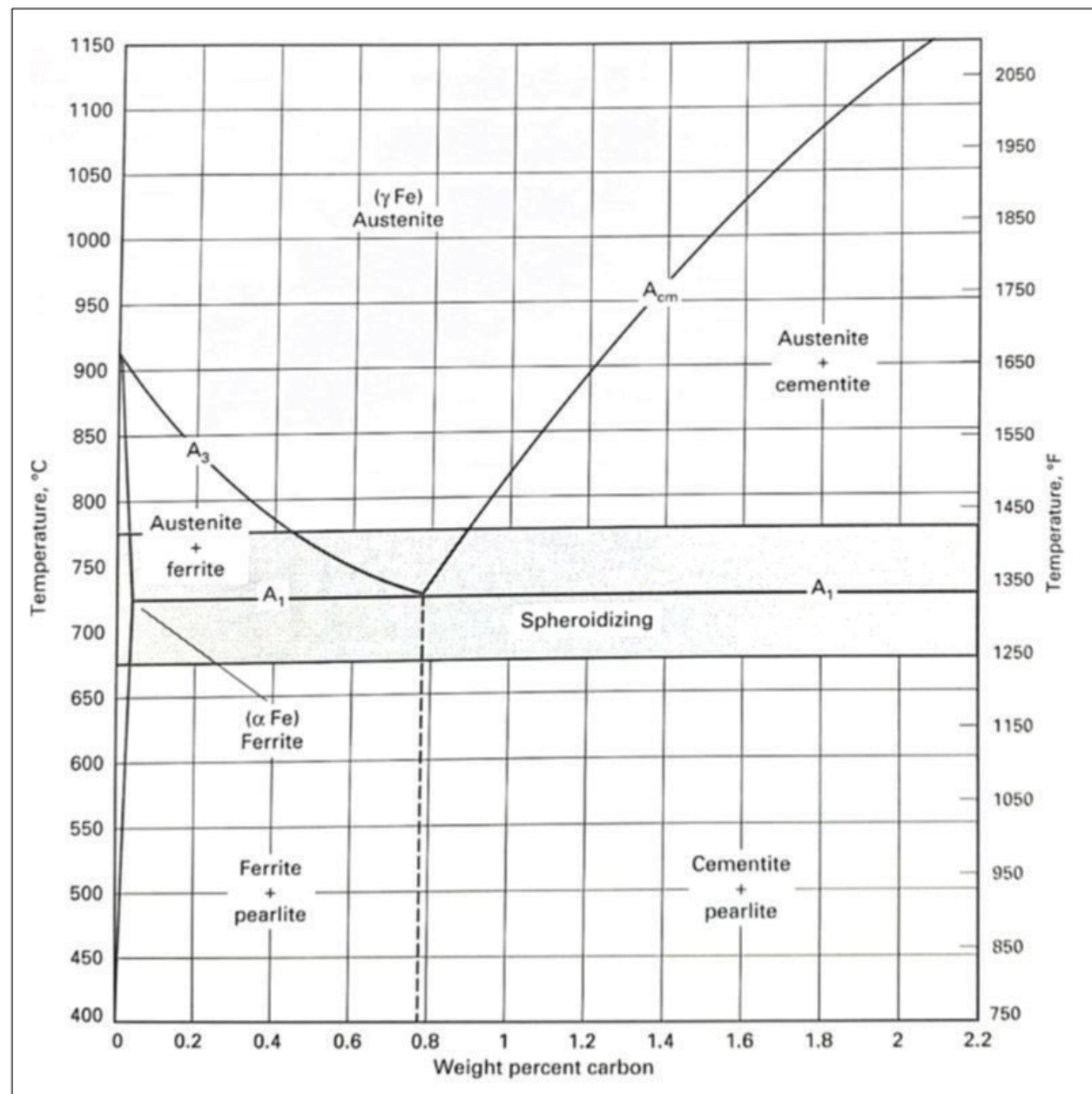
The Iron-Carbon Phase Diagram



The iron-carbon phase diagram is used to understand how carbon content and temperature affect the phases present in steel at **equilibrium**.

The diagram features several critical regions:

- Liquid phase** - where steel exists as molten metal
- Austenite region** - stable at high temperatures
- Ferrite region** - low temperature iron-rich phase
- Cementite region** - carbon-rich phase
- Mixed regions** - where multiple phases coexist



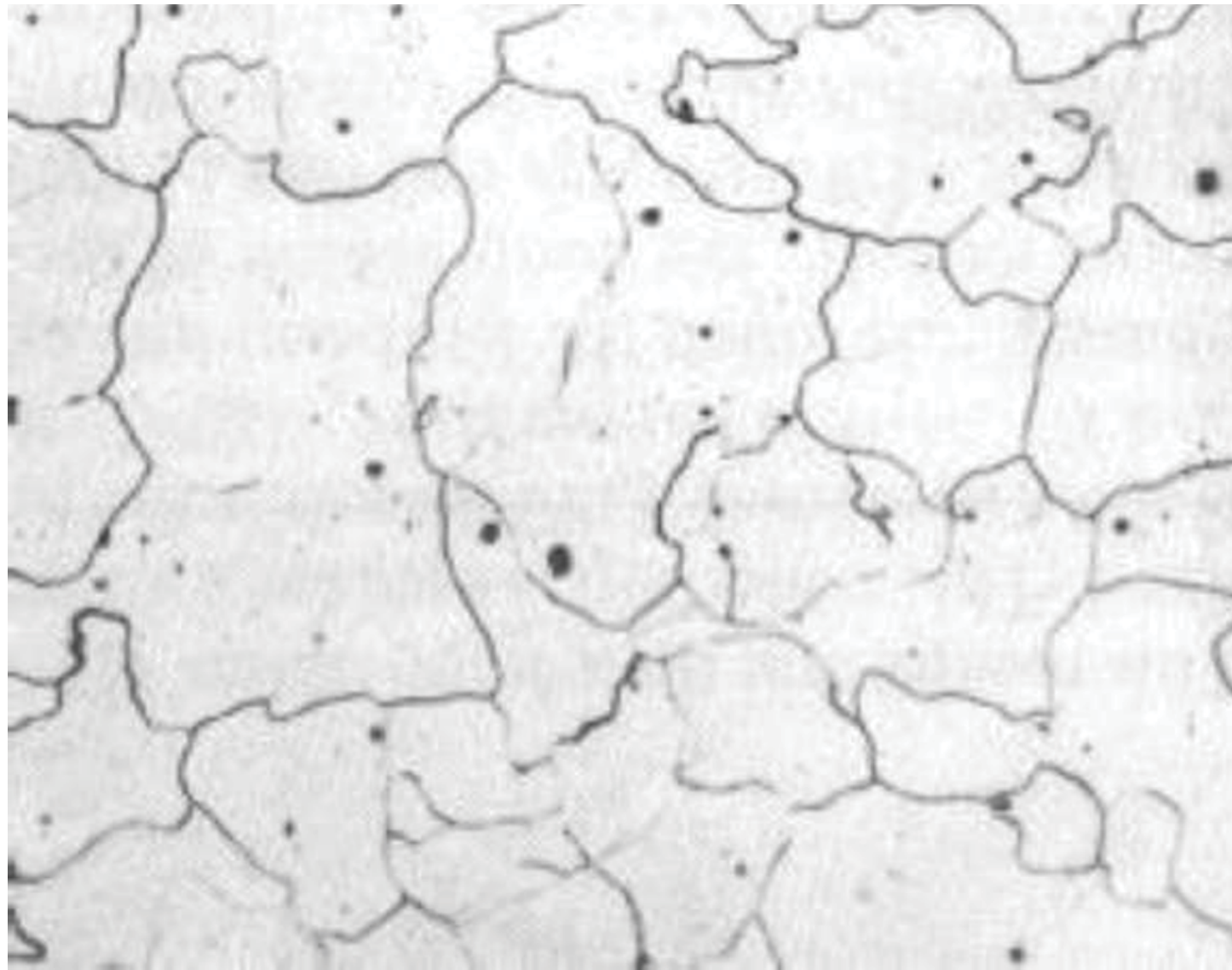
Austenite is the FCC form of iron and can dissolve substantially more carbon than ferrite.

Forming when steel is heated to a critical temperature, austenite is important because many common hardening treatments begin by converting the steel to austenite.

Austenite can transform into ferrite, pearlite, bainite, or martensite depending on composition and cooling conditions.

Some austenite can remain after cooling and is called retained austenite

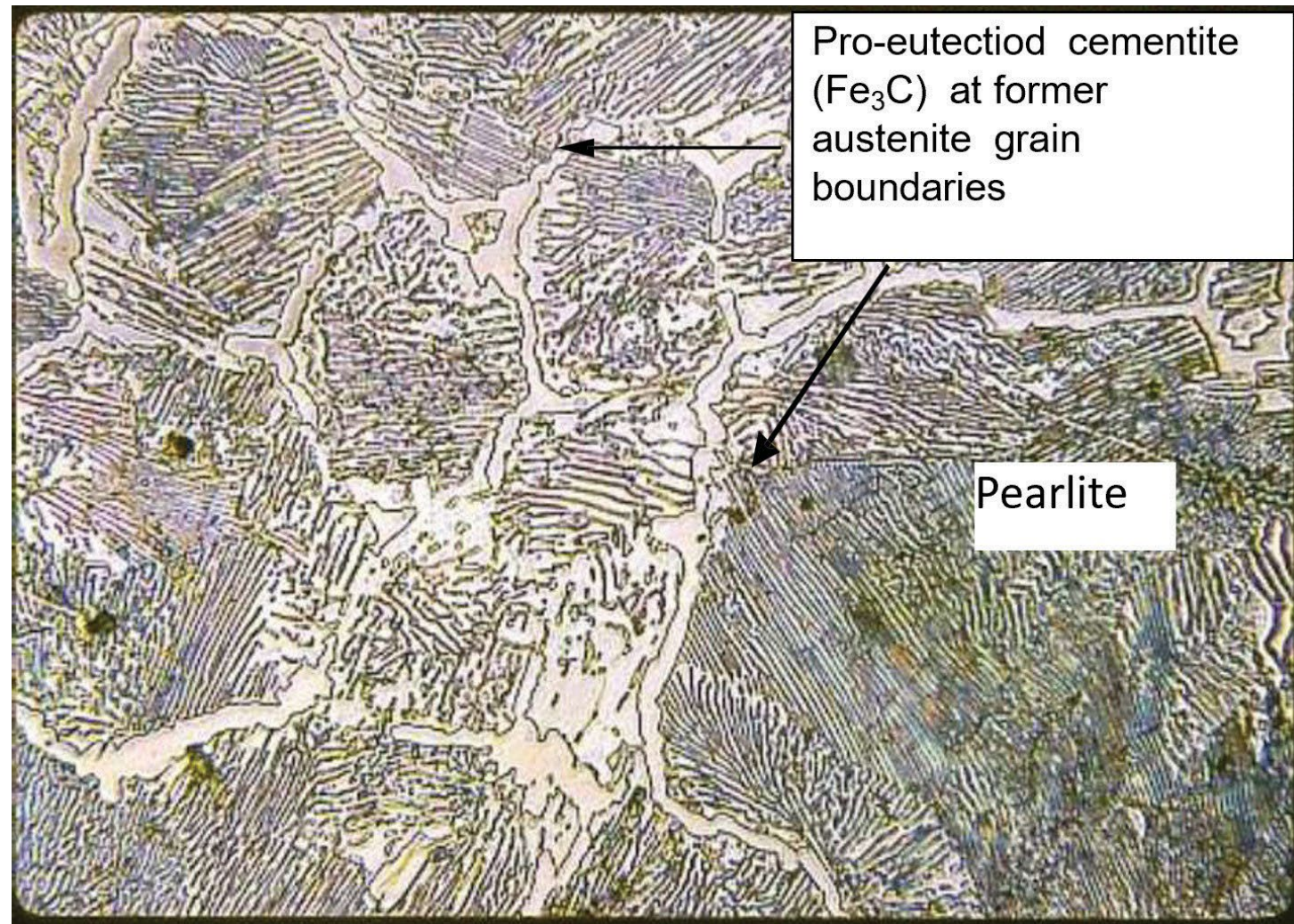
Ferrite



Ferrite is a relatively soft, ductile phase of iron containing a relatively small amount of carbon.

- **Alpha ferrite (α -ferrite)** has a body-centered cubic (BCC) crystal structure. It is stable at lower temperatures in plain-carbon steels.
- **Delta ferrite (δ -ferrite)** is a BCC form of iron that forms at high temperatures during solidification and can occur in some alloy steels.

Cementite

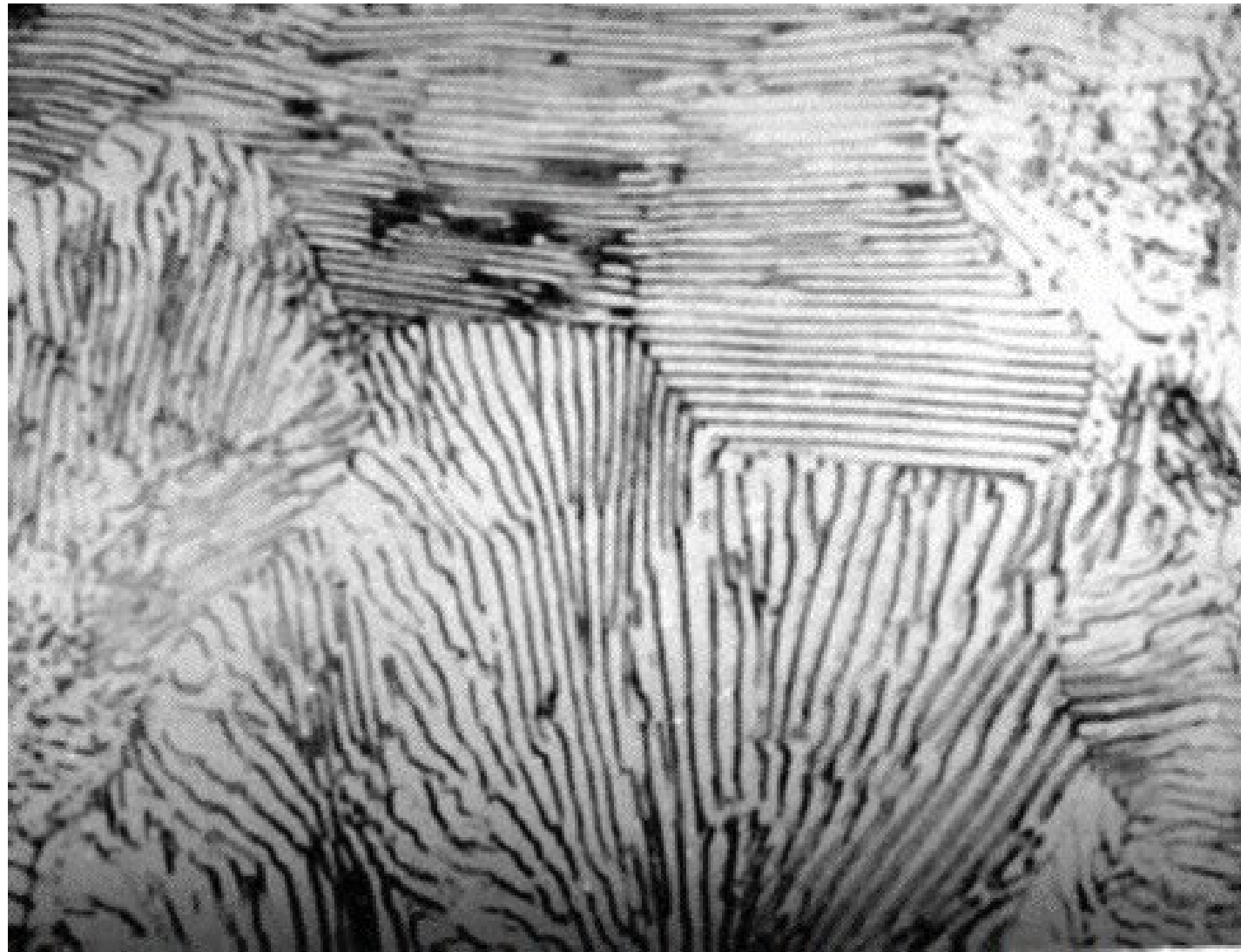


Cementite (Fe_3C) is formed from a reaction when excess carbon exceeds the solubility limit of ferrite during a slow cooling from austenite.

Cementite is an important component of pearlite and other steel microstructures.

The amount and distribution of cementite influence the hardness and strength of steel.

Pearlite



Pearlite forms when austenite undergoes eutectoid transformation (when a solid phase decomposes into 2 different solid phases) under relatively slow cooling conditions.

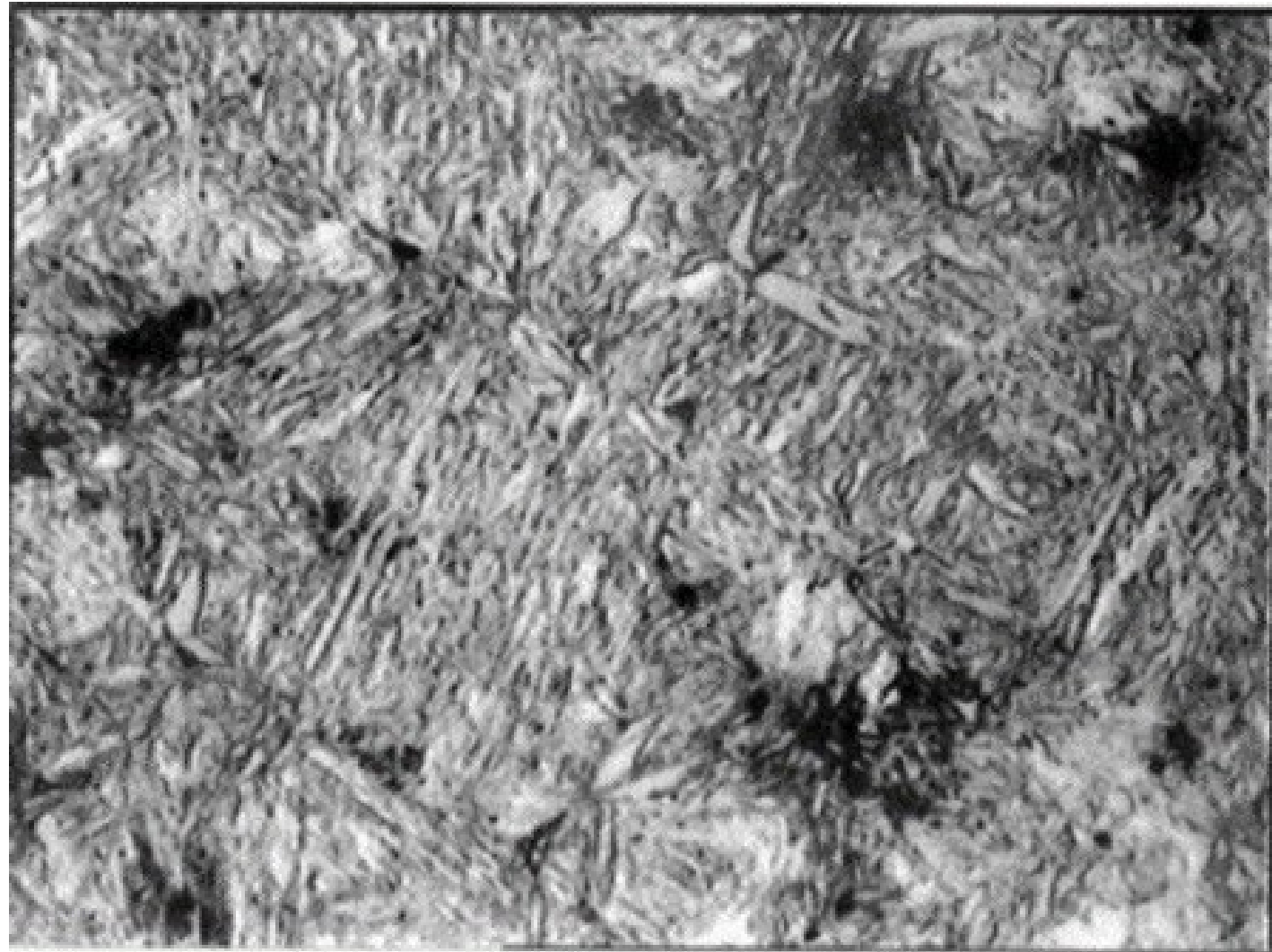
Pearlite consists of alternating layers of:

- Ferrite**
- Cementite**

Pearlite can be:

- Fine pearlite – thinner, more closely spaced layers
- Coarse pearlite – thicker, more widely spaced layers

Bainite



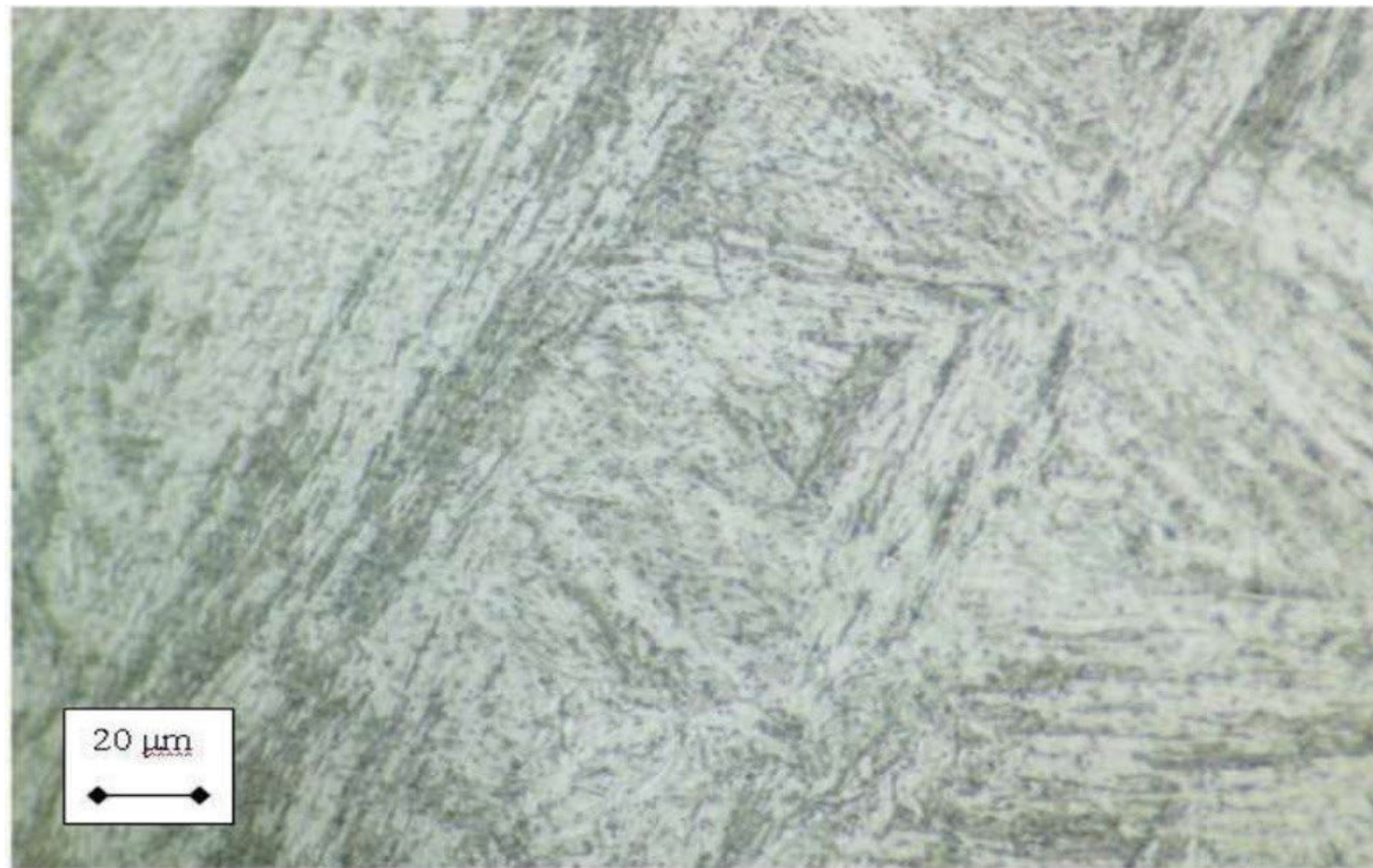
Bainite forms from austenite when cooling rates are slower than martensite but faster than ferrite or pearlite.

Bainitic transformation involves both diffusion and shear mechanisms.

Bainite is commonly classified as:

- Upper bainite
- Lower bainite

Martensite



Martensite forms when austenite is cooled rapidly enough to suppress diffusion-controlled transformations.

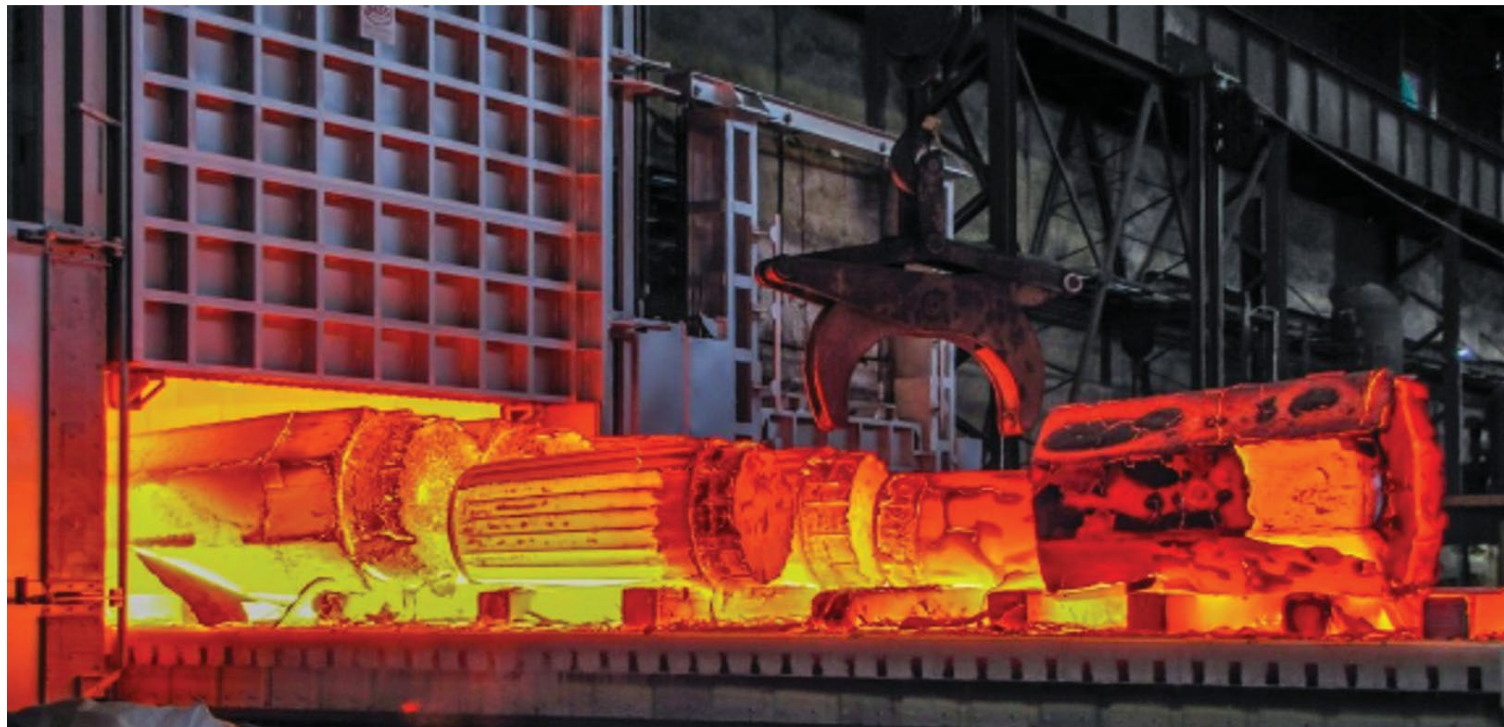
Martensite has a body-centered tetragonal (BCT) structure in carbon steels.

Carbon becomes trapped in the crystal structure, producing significant lattice distortion.

Martensite can be tempered to reduce hardness and brittleness, causing carbon to redistribute.

Heat Treatment of Steel

What is the Heat Treatment of Steel?



Parts heated in a furnace

Heat Treating is a process involving controlled heating and cooling of a material, like steel, to alter or change its properties.

Steel parts can be made harder or softer, stronger, tougher, or more ductile with different heat treatment processes.

How Heat Treating Changes Properties

During heat treat, steels are heated and quenched through critical temperatures.

Phase transformations occur resulting in a microstructure and phase change that alters the material properties of the steel.

The heating and cooling rates, temperatures, and hold times all influence the final microstructure and properties.

Steels are typically heat treated for:

- Softening** – reduce strength or hardness, improve ductility/toughness for better machinability
- Hardening** – increases strength, hardness, wear resistance
- Composition modification** – alters chemical composition for enhanced properties



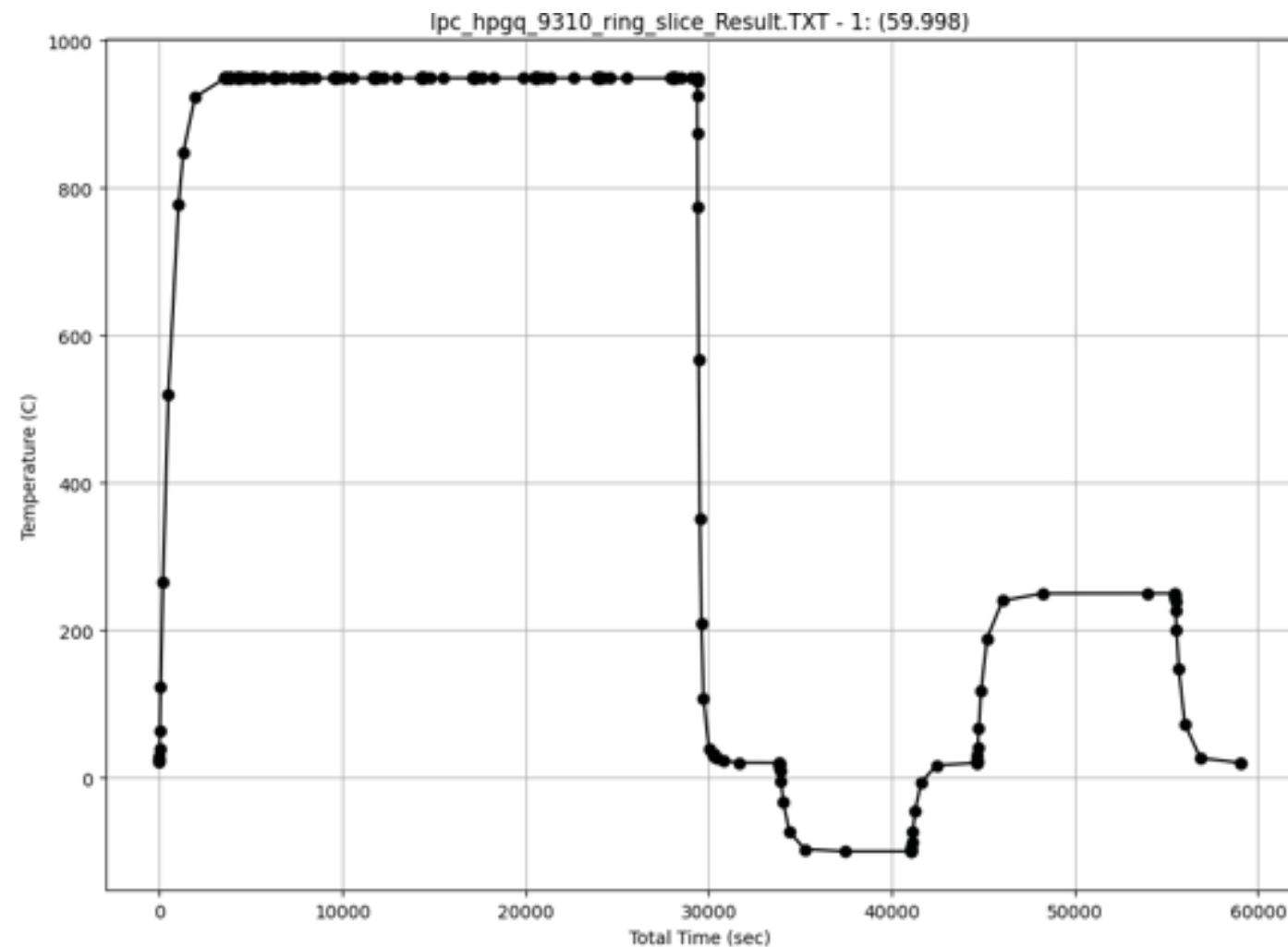
Material Properties



Properties that can be affected include:

- Hardness** – ability to withstand surface indentation (localized plastic deformation). Measured in Hardness Rockwell C scale for steels, also Vickers, Brinell, Knoop, etc.
- Strength** – each microstructural phase has a different associated yield strength
- Ductility** – ability to withstand plastic deformation without rupture
- Toughness** – ability of a material to absorb energy and plastically deform without fracturing
- Workability** – capacity of steel to deform without cracking during metalworking processes
- Corrosivity** – certain thermo-chemical heat treatment processes can improve corrosion resistance

The Heat Treating Process Overview



Heat treatment typically consists of:

- **Heating/"austenitizing"** – bringing the material to a desired temperature Holding/soaking maintaining the material at that temperature for a specified time
- **Cooling/quenching** – cooling the workload in a quenching media
- **Tempering** - reheating a hardened steel to a lower temperature to reduce brittleness, hardness, and relieve stresses

Other processes include annealing, normalizing, cryogenic treatment (deep freeze), carburizing, nitriding, or induction hardening

Steel Hardenability

Why do different steels produce different and varying depths of hardness for a given quench?

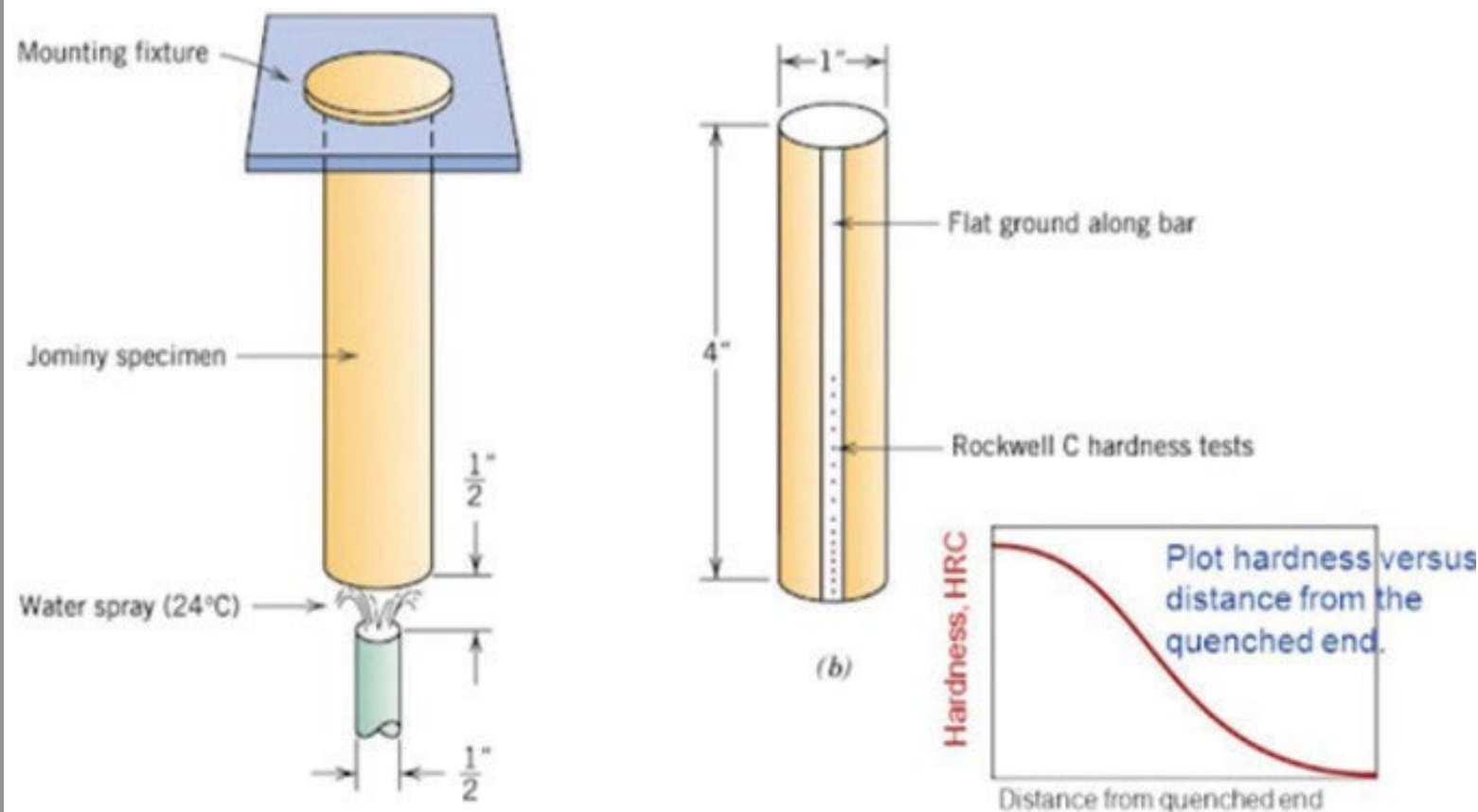
Hardenability – The ability of a steel to form martensite at a given depth during a quench

Higher hardenability steels more easily form martensite – carbon & alloying elements greatly impact hardenability

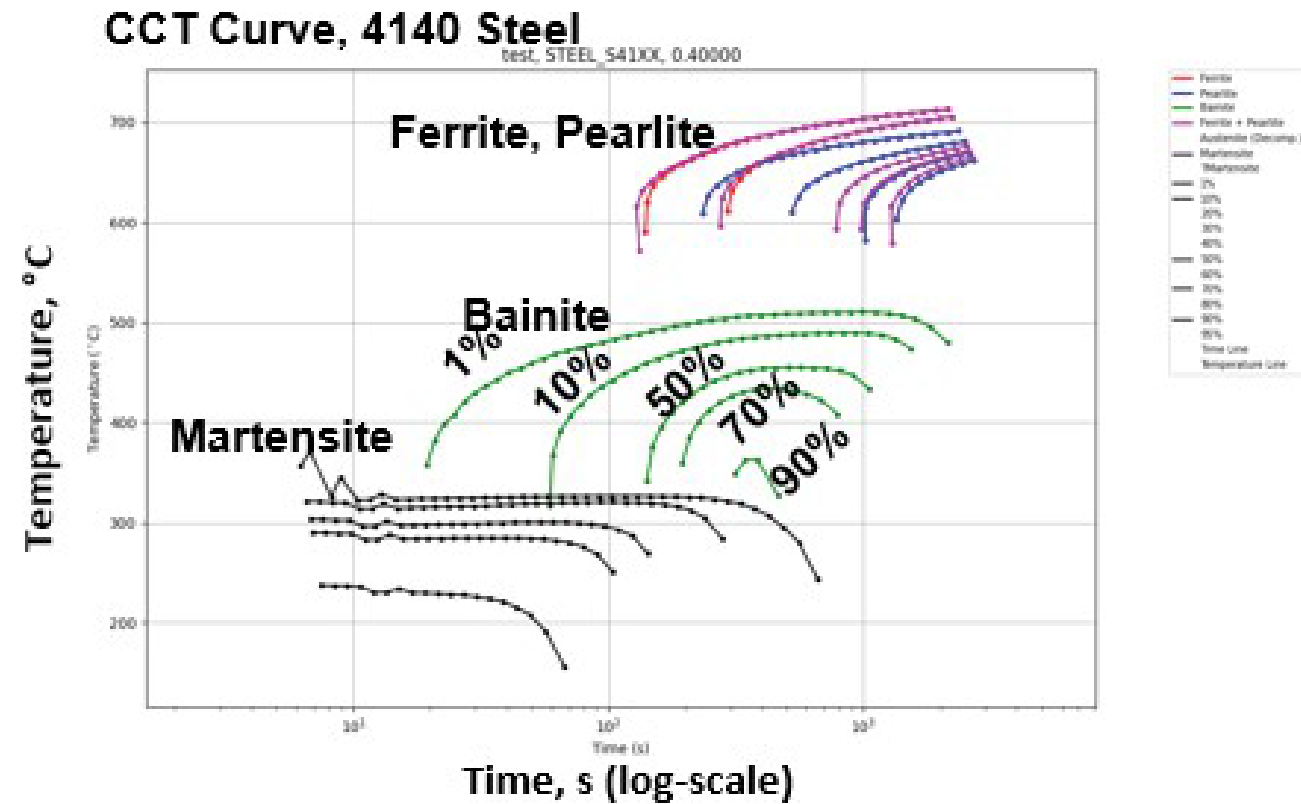
Different methods are available to compare hardenability of steels:

- Jominy end quench test – measures hardness vs distance from quenched end

- Ideal Diameter (DI) - max diameter possible to achieve 50% martensite in the bar center for an ideal quench



TTT & CCT Diagrams



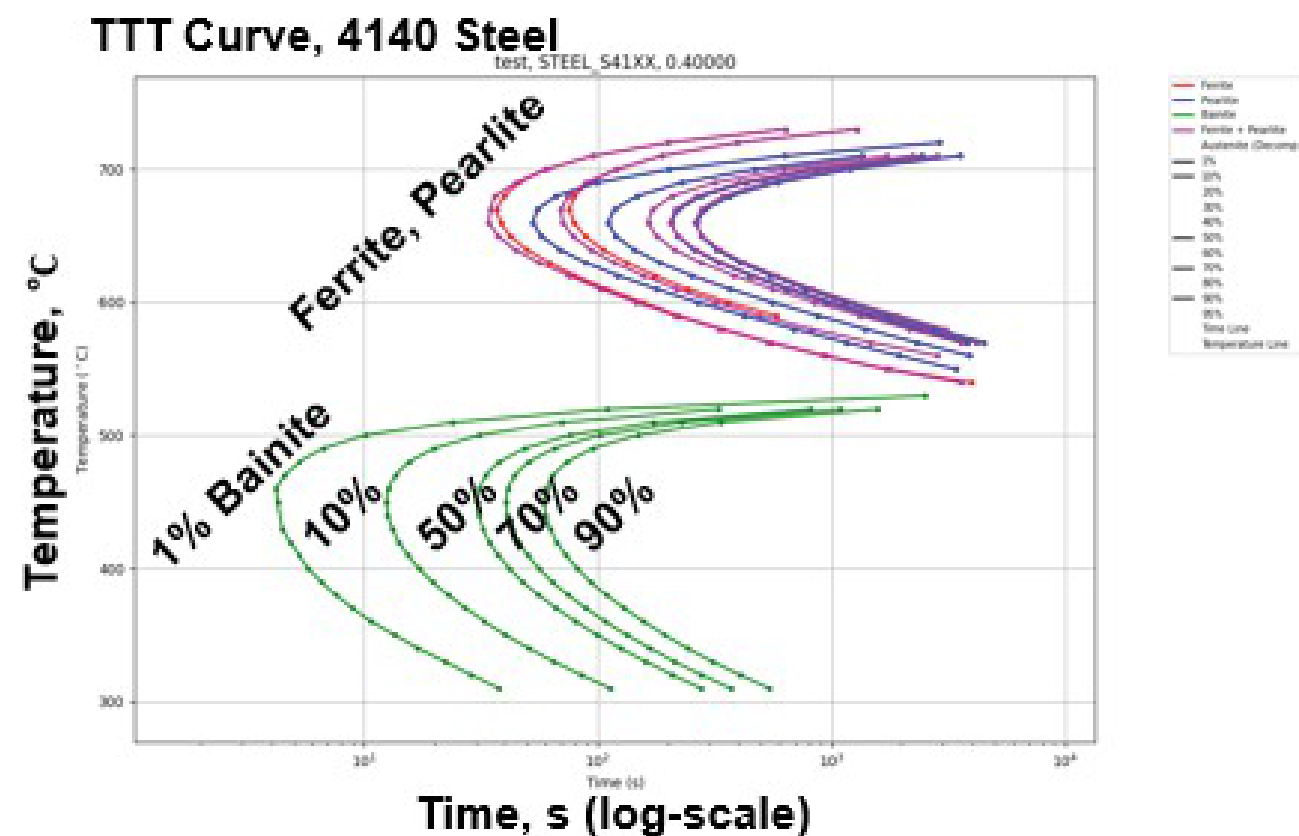
What happens to austenite when steel is cooled at different rates?

TTT & CCT diagrams show how austenite transforms during cooling and how cooling rate affects microstructure

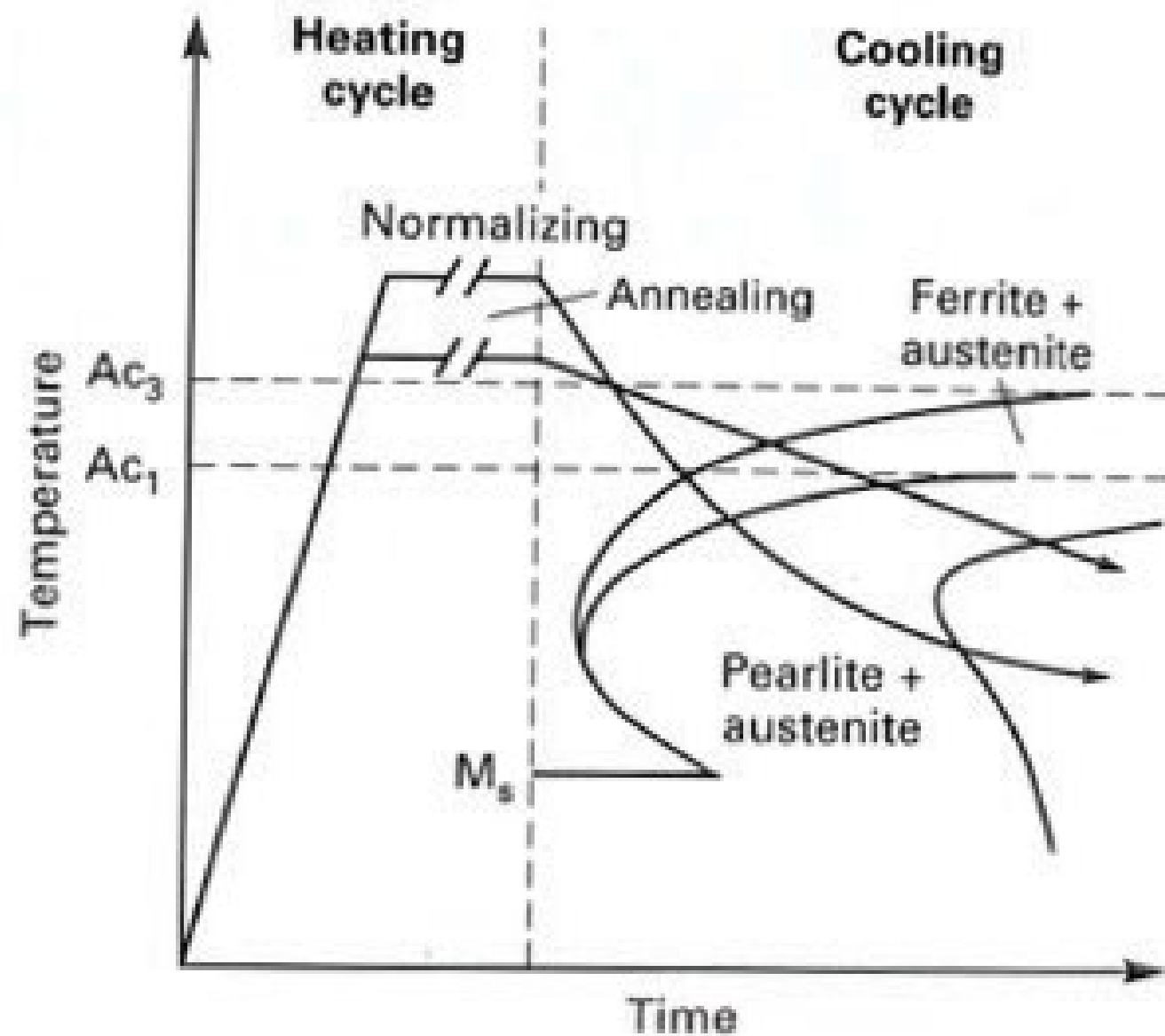
TTT (Time-Temperature-Transformation) - shows transformation of austenite when held at a constant temperature (isothermal)

CCT (Continuous Cooling Transformation) - shows transformations in continuously cooled steel

Curves show when different phases start to form at given temperatures and times



Common Heat Treatment Processes



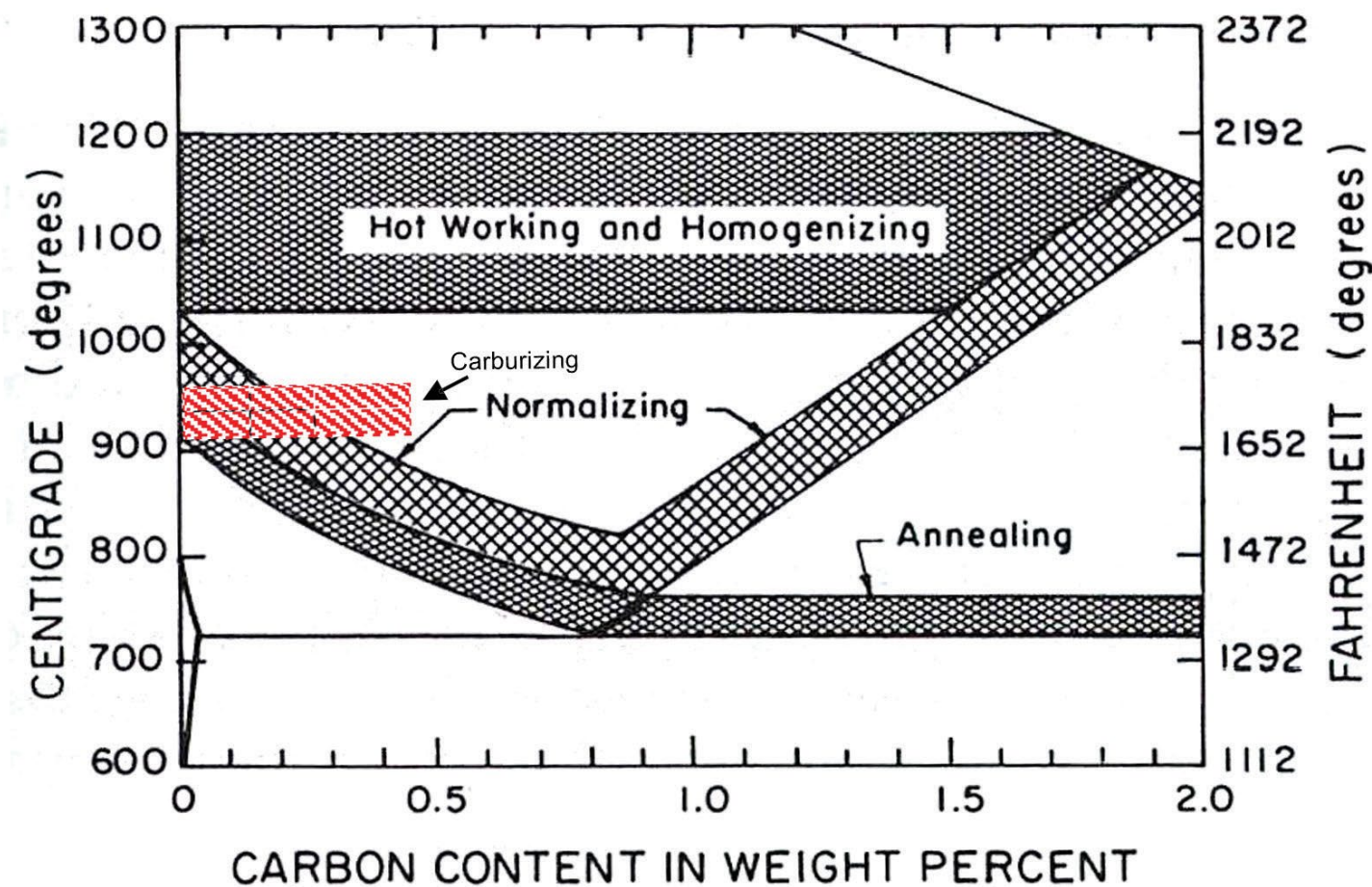
Annealing is heating to a specific temperature, holding at that temperature, then cooling at a specific rate.

Softening the material is the main goal of annealing

Types of annealing:

- Subcritical annealing (below Ac_1)
- Austenite is not formed
- Recovery, recrystallization and carbide growth
- Intercritical annealing (above Ac_1 but below Ac_3)
- Austenite begins to form above Ac_1
- Mixture of Ferrite and Austenite slowly homogenizes
- Increased carbon solubility

Normalizing



Normalizing involves austenitizing steel followed by air cooling.

Normalizing can be used to:

- Refine and homogenize grain structure
- Improve machinability
- Reduce residual stress

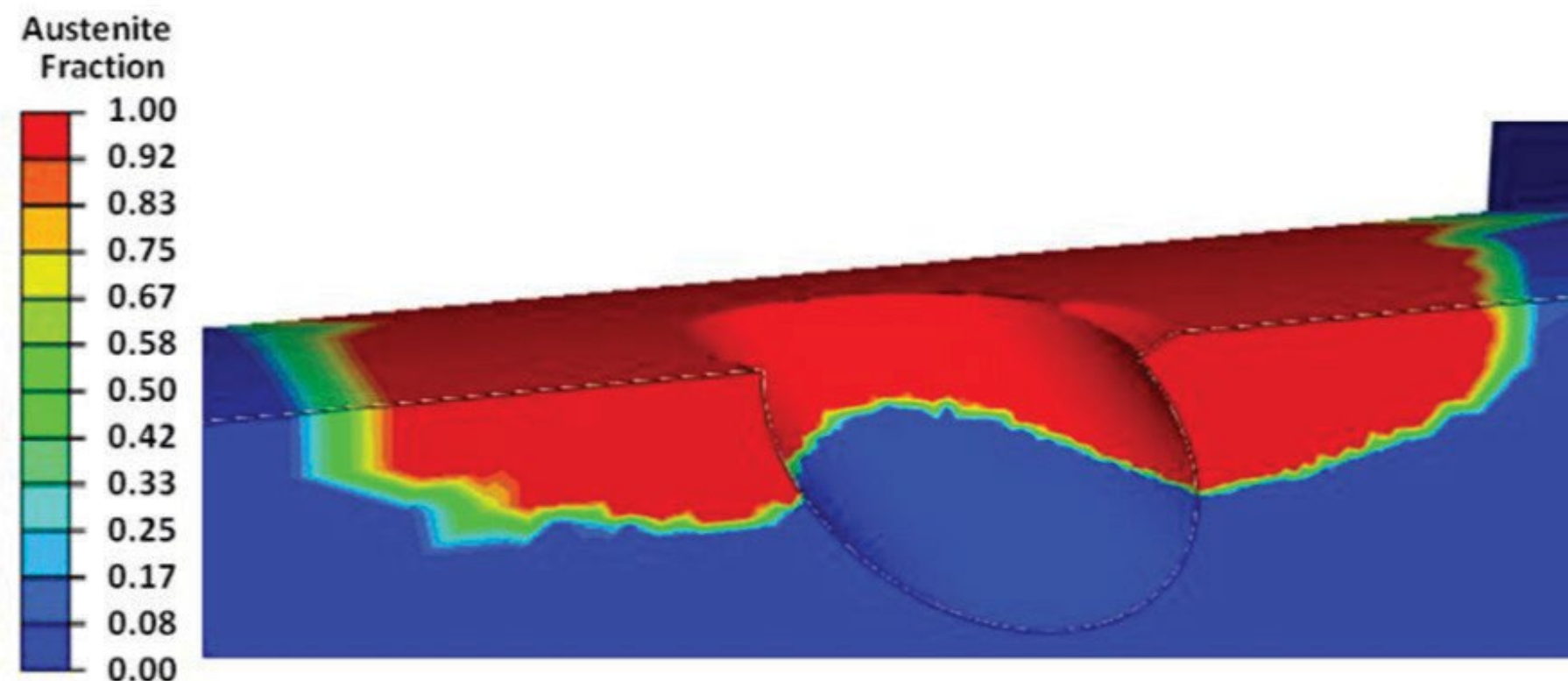
Annealing and Normalizing are similar processes with different purposes

Austenitizing

Austenitizing is raising the temperature of a steel beyond its critical temperature for long enough to fully transform to austenite.

When an austenitized material is cooled rapidly from Austenite temperatures, it is considered quenched.

Depending on the type of quenching, different phases will result due to the difference in cooling rate.



Quenching



Part being immersed into oil quench tank,
Shakti Heat Treaters

Quenching is the rapid cooling of a material from an elevated temperature.

Common quench media include:

- Water
- Oil
- Polymer
- Air/gas

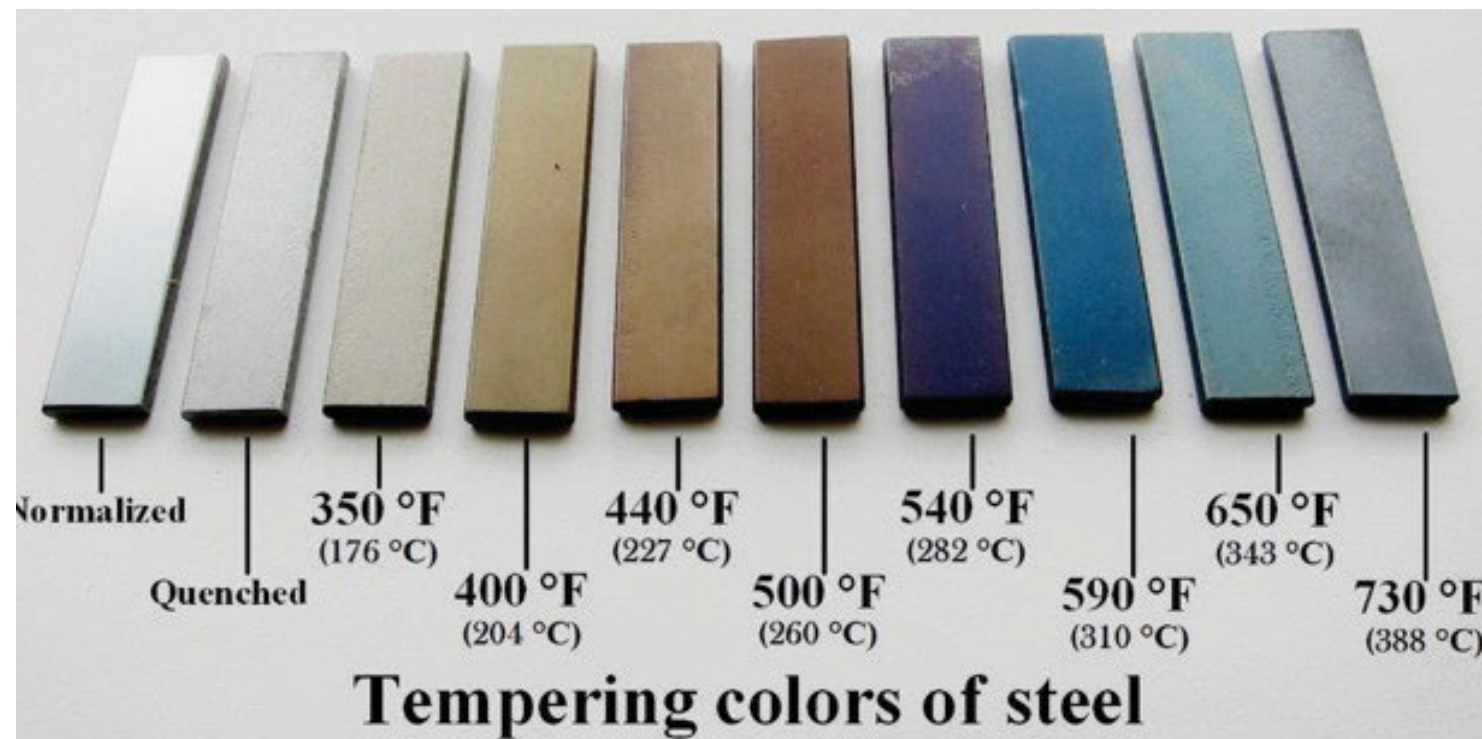
If the **Martensite start temperature** is reached fast enough during quenching, martensite can form.

Faster quenching generally increases the likelihood of forming martensite.

Quenching can also introduce:

- Residual stresses
- Distortion
- Cracking

Tempering



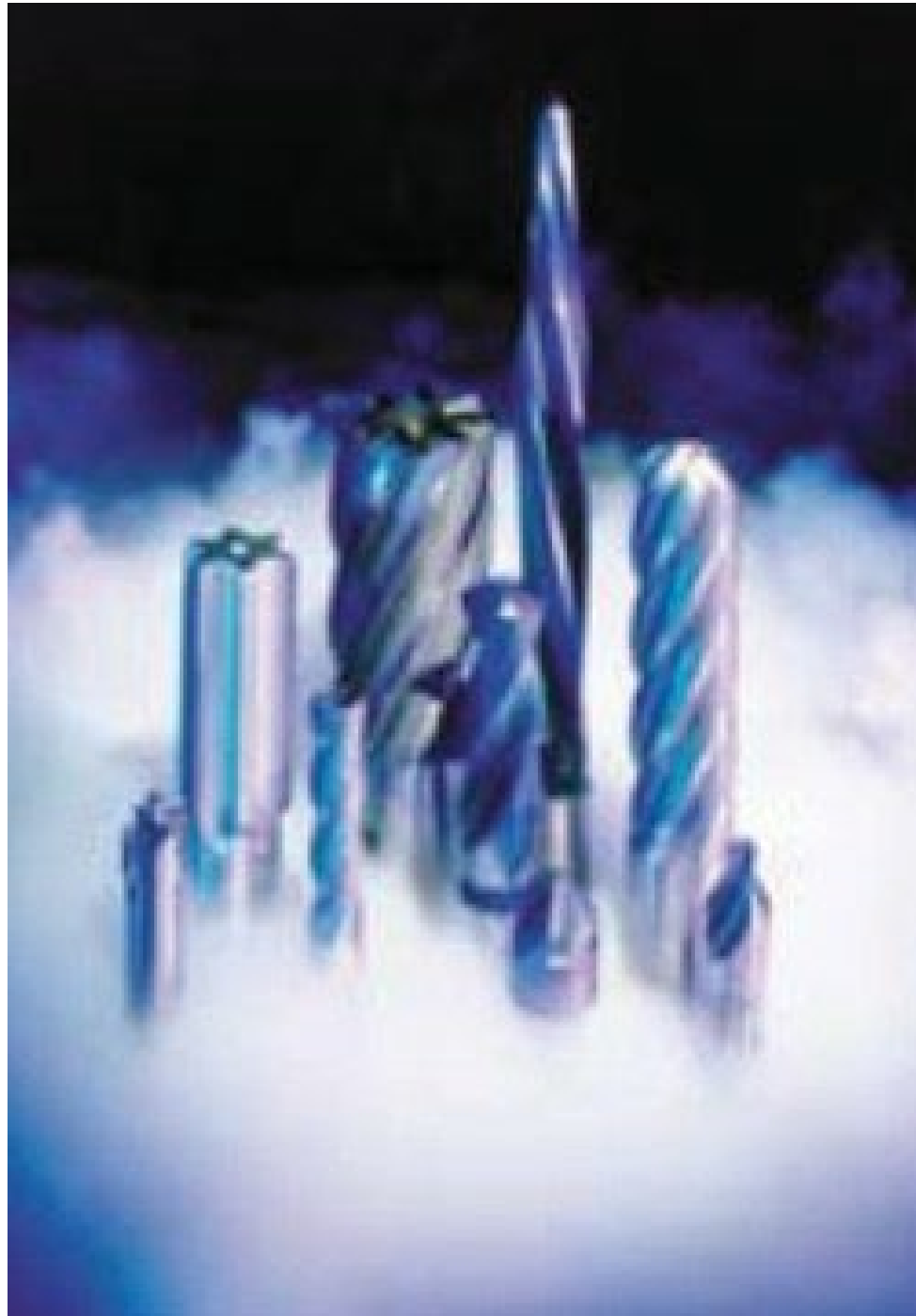
Tempering is a heat treat process where hardened steels are reheated below transformation temperatures.

Reduces hardness and brittleness of martensite by allowing carbon to redistribute.

Increases ductility, toughness, and can reduce residual stresses.

Typical processing temperature ranges from 150-650°C depending on alloy and desired properties.

Cryogenic Treatment



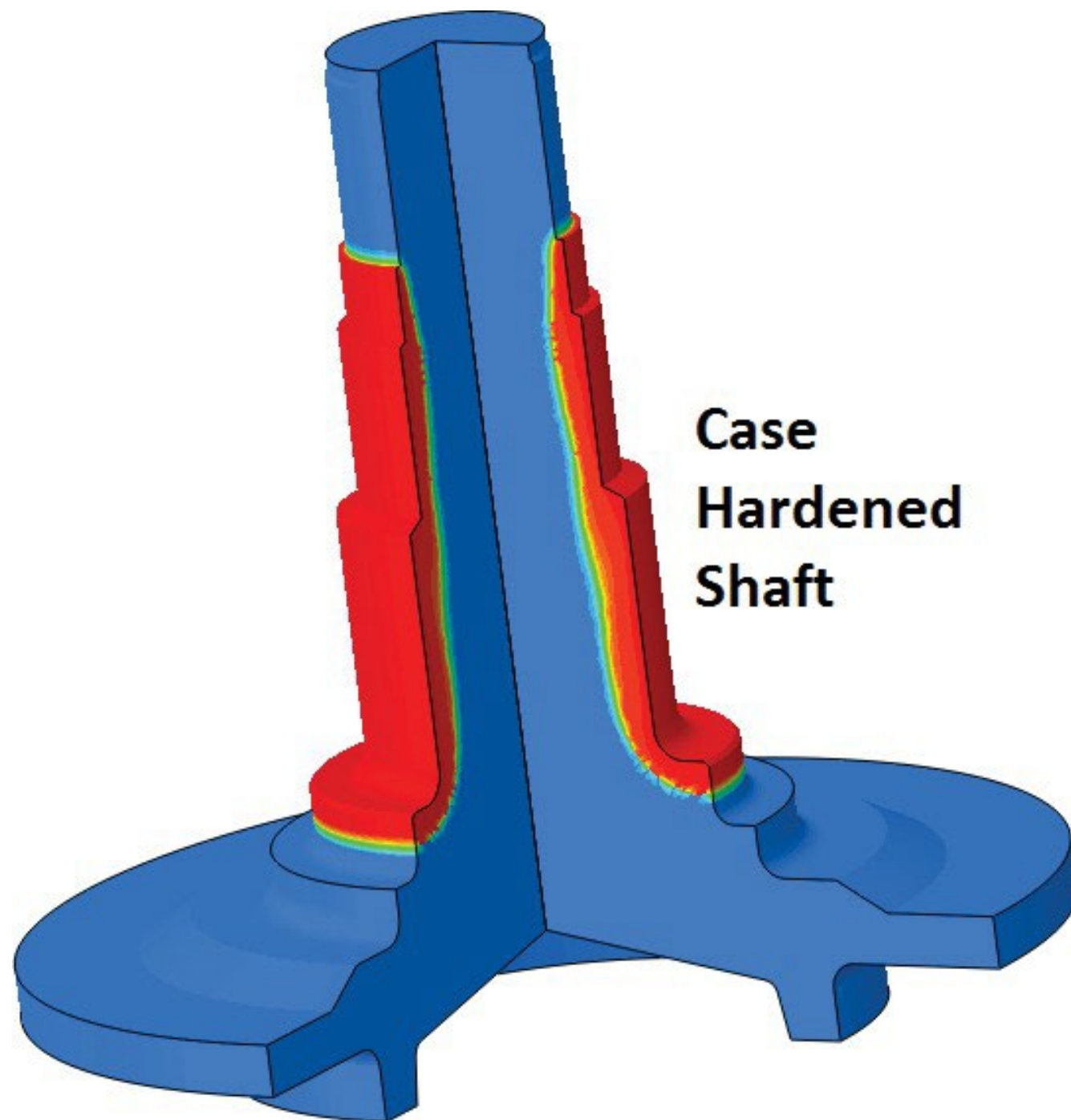
Cryogenic treatment or deep freezing is a process where steel is cooled to low temperatures around -80 to -200°C

Typically applied after quench hardening and before tempering

Quenching can leave retained austenite and deep freezing can help transform it to martensite

Improves microstructure and dimensional stability

Case Hardening



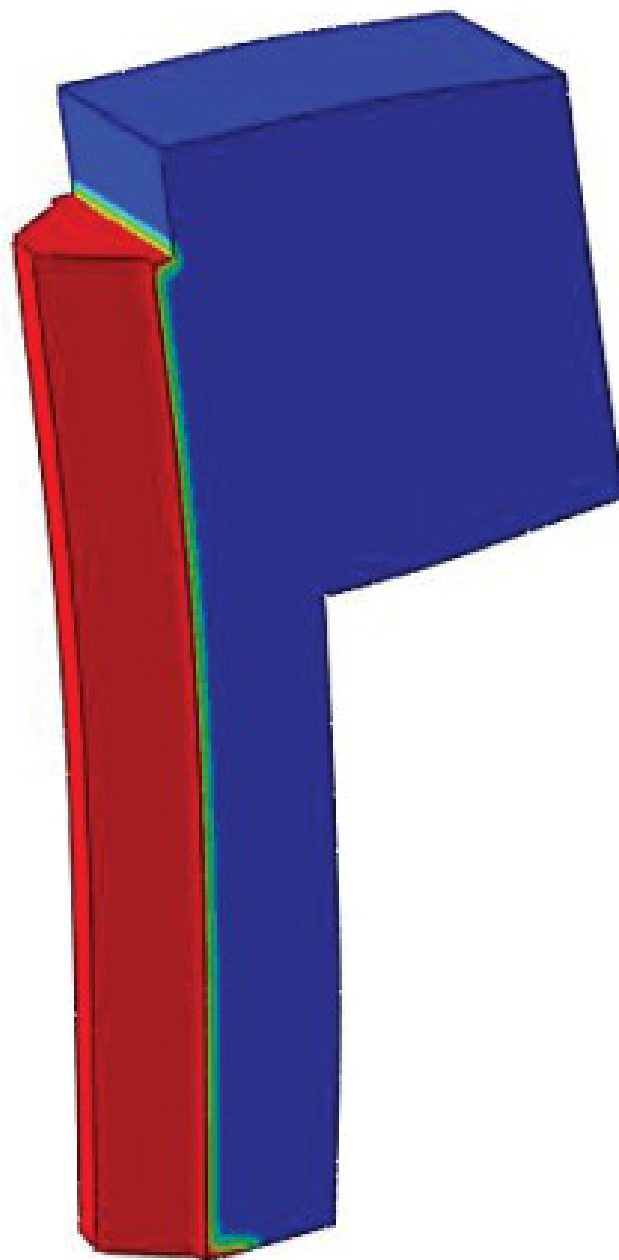
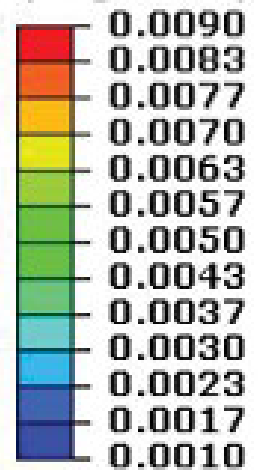
Case hardening focuses on developing a hardened surface while maintaining a tough core

Thermal methods like induction heating or flame hardening heat the near surface of the part past its critical temperature, allowing for phase transformation when quenched

Thermochemical methods like carburizing or nitriding diffuse carbon or nitrogen into the surface, altering the near surface properties.

Case carburized gear tooth model
showing the carburized layer and
carbon gradient

SDV_CARBON
(Avg: 75%)



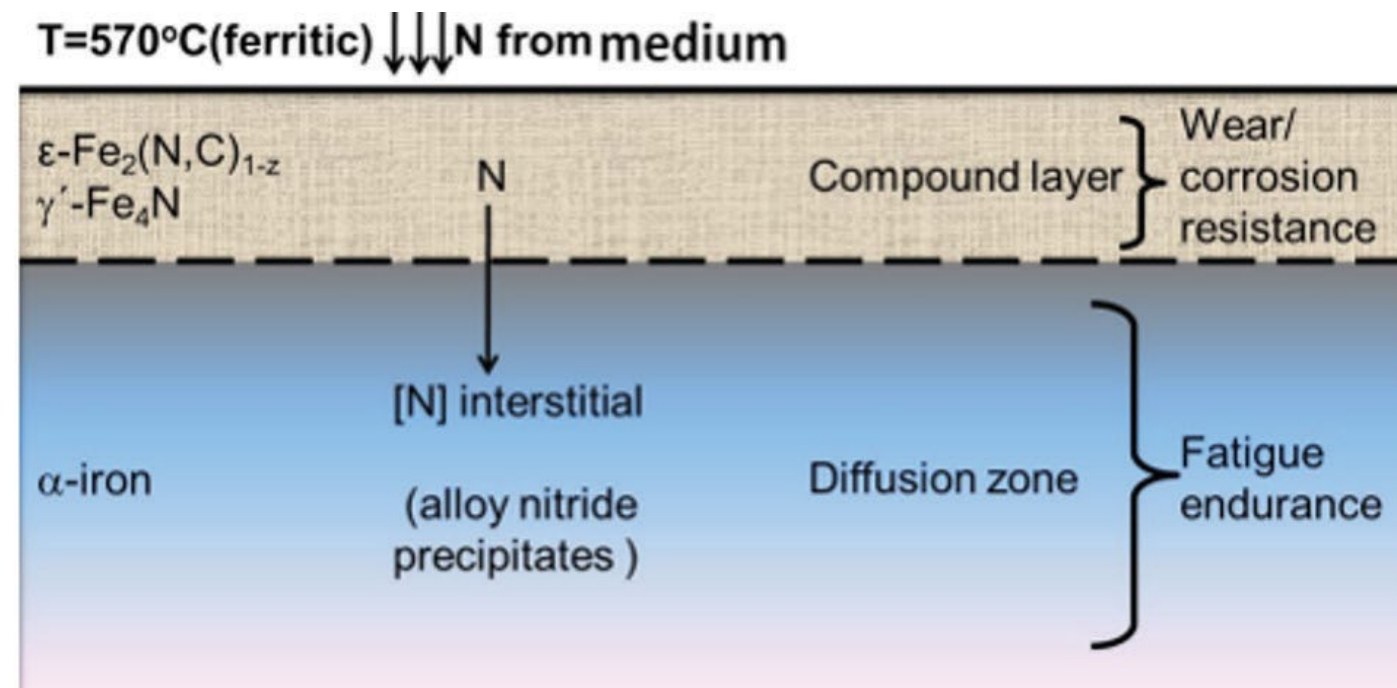
Carburizing is a case hardening process that increases the carbon concentration at the surface of a steel component.

The steel is heated into the austenitic region while exposed to a carbon-rich environment diffusing carbon into the surface.

Carburizing produces a hard, wear-resistant surface with compressive surface residual stress

The tougher, lower-carbon core has balancing tensile stress

Nitriding



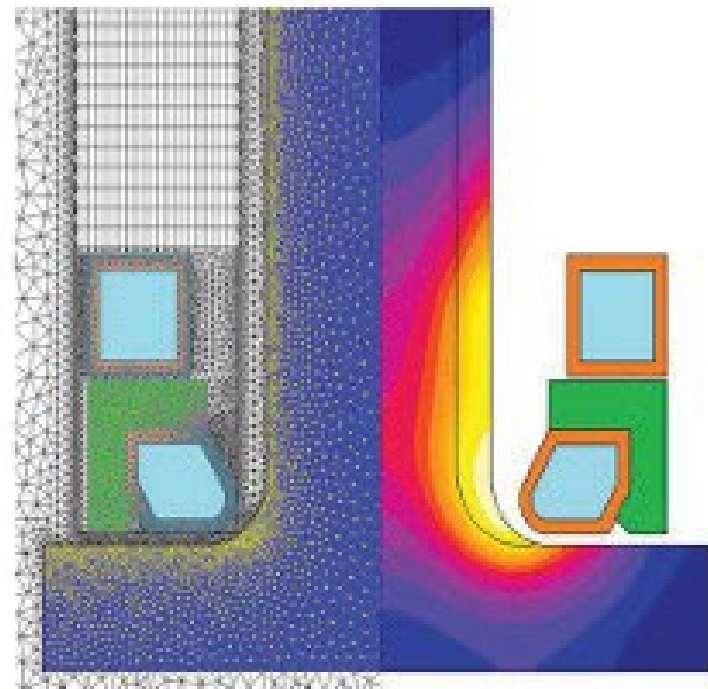
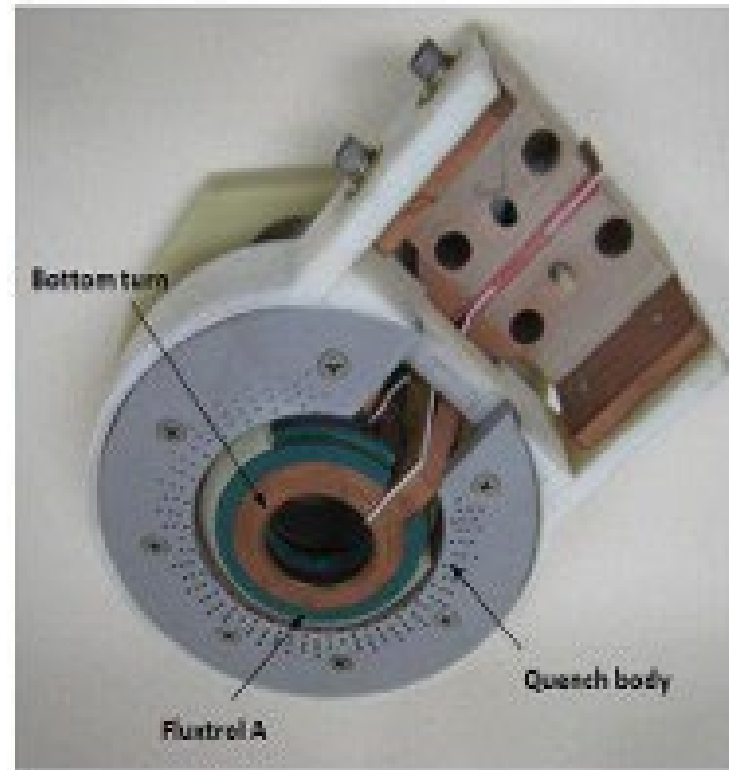
Nitriding case is comparatively shallow and can readily form a “white layer” of iron nitrides or compounds of nitrogen and iron on the steel surface

Nitriding, similar to carburizing, is a case hardening process that increases the nitrogen concentration at the surface of a steel component.

Steels are typically heated to around $500\text{-}600^{\circ}\text{C}$ while exposed to a nitrogen-rich environment diffusing nitrogen into the surface.

Nitriding produces high surface hardness and wear resistance.

Induction Hardening



inductor design and EM Modeling by Fluxtrol, Inc

Induction hardening uses electromagnetic induction to heat steel components.

Alternating current passes through an induction coil and generates an alternating magnetic field.

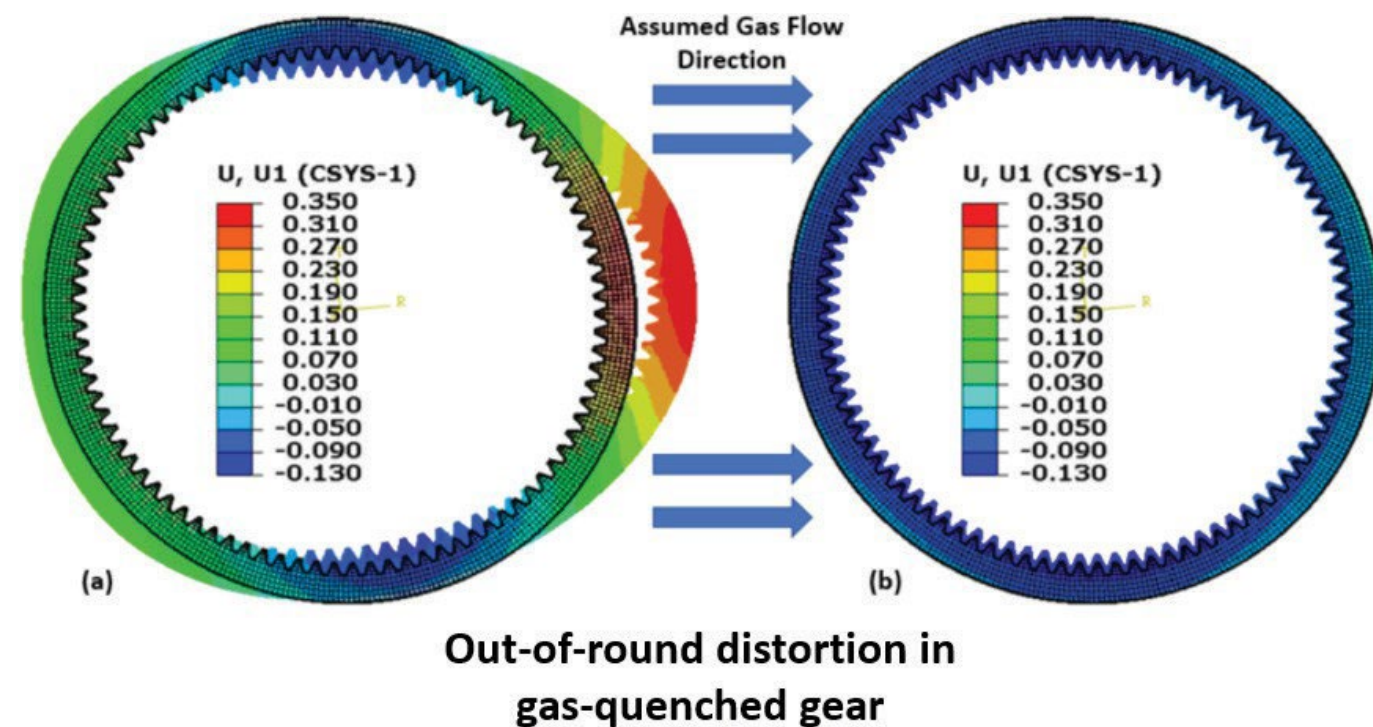
Eddy currents are induced in the component, producing heat. Quenching this localized heated region produces a hard martensitic surface while retaining a tougher core.

It is commonly used for components such as:

- Gears
- Bearings
- Shafts
- Automotive components

Common Issues in Heat Treatment

Distortion



Distortion is a change in the part shape or dimensions from heat treatment

Plastic deformation caused by non-uniform phase transformation and thermal strains

Uneven heating and cooling produces non-uniform thermal phase transformation gradients

Distortion includes both size and shape change like bowing, bending, twisting, warping, out-of-round or other dimensional changes

Excessive distortion results in scrapped parts

Non-uniform Hardness



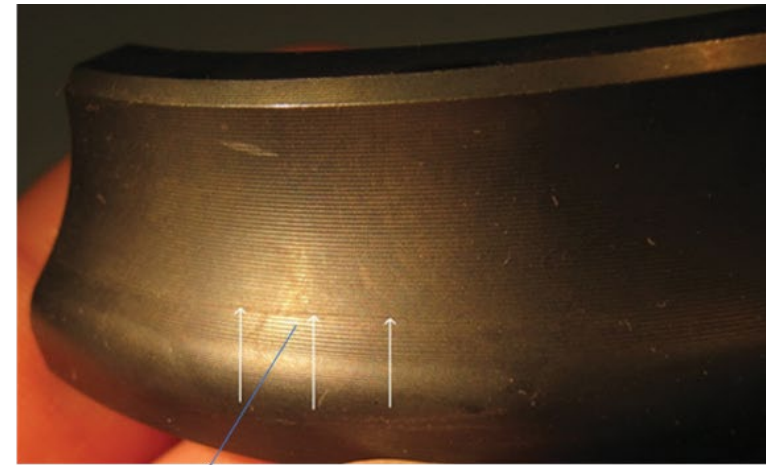
Components do not always heat or cool uniformly.

Differences in temperature throughout a component can produce thermal gradients.

Thermal gradients can contribute to:

- Residual stress
- Distortion
- Cracking
- Non-uniform microstructures
- Non-uniform hardness

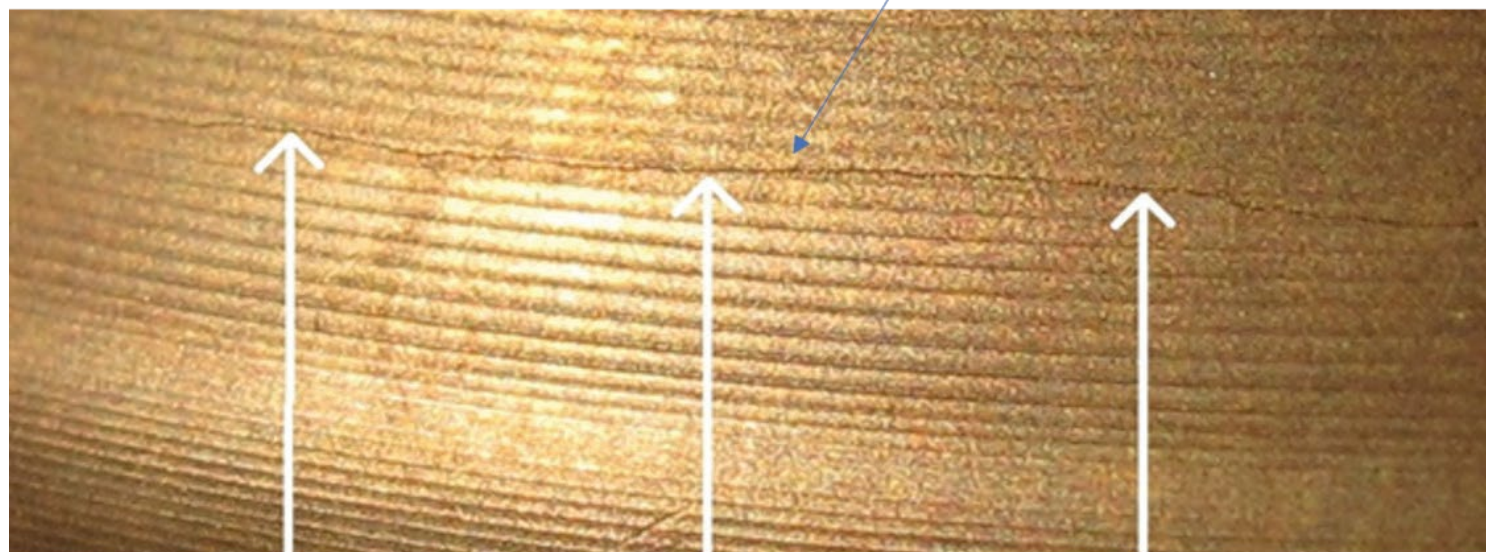
Quench Cracking



Cracking during or shortly after quenching can occur when thermal and transformation stresses become sufficiently large.

Cracking may occur due to a combination of:

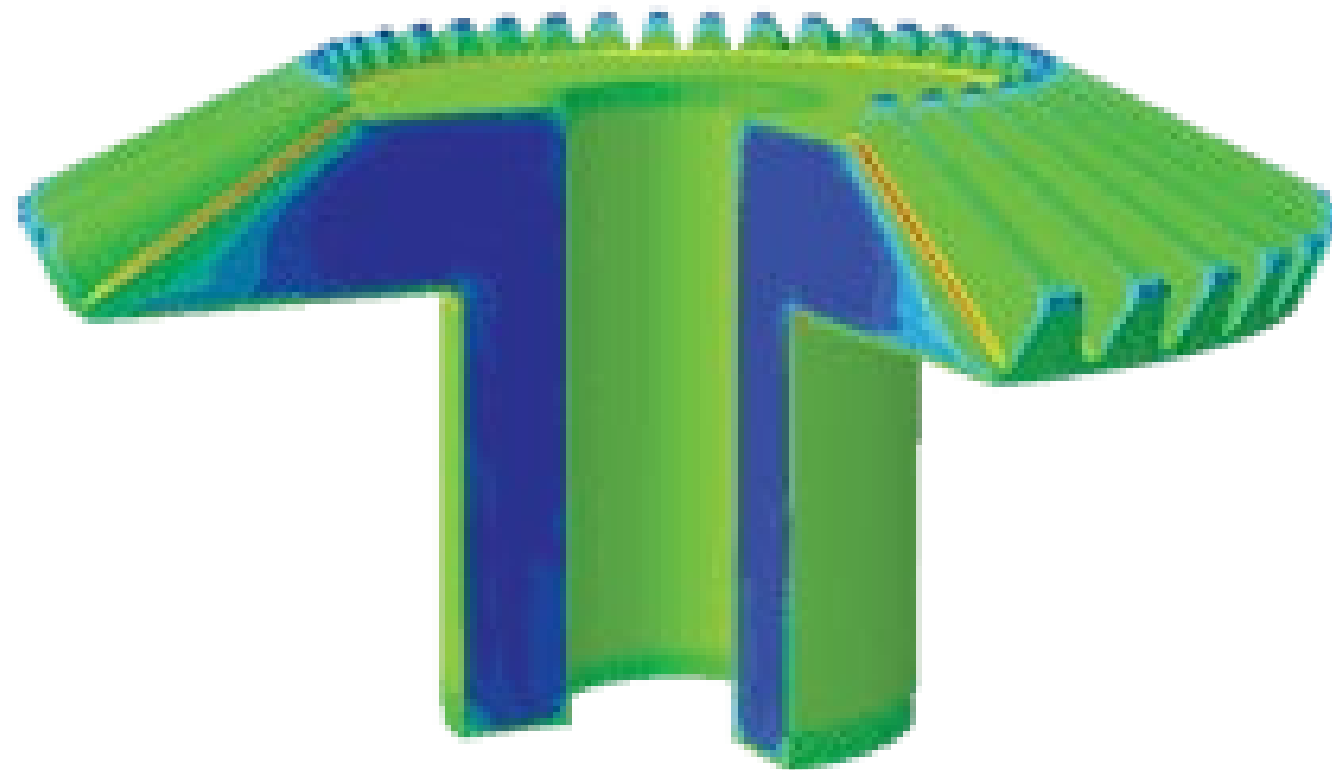
- Rapid cooling resulting in large thermal gradients
- Relative volume expansion and contraction from non-uniform phase transformations
- Geometric stress concentrators from sharp corners, holes, etc.



Magnified view of bearing race crack

Quench cracking results in scrapped parts.

Residual Stress



Residual stress:

- Is stress that remains in a part when no external loading is present
- Can cause distortion or cracking in-service
- Can result from nonuniform thermal and phase transformation gradients
- Creates a balance of tensile and compressive stresses
- In properly case hardened components, surface compressive residual stresses can be beneficial to fatigue life

Decarburization



Decarburization is the loss of carbon from the steel surface

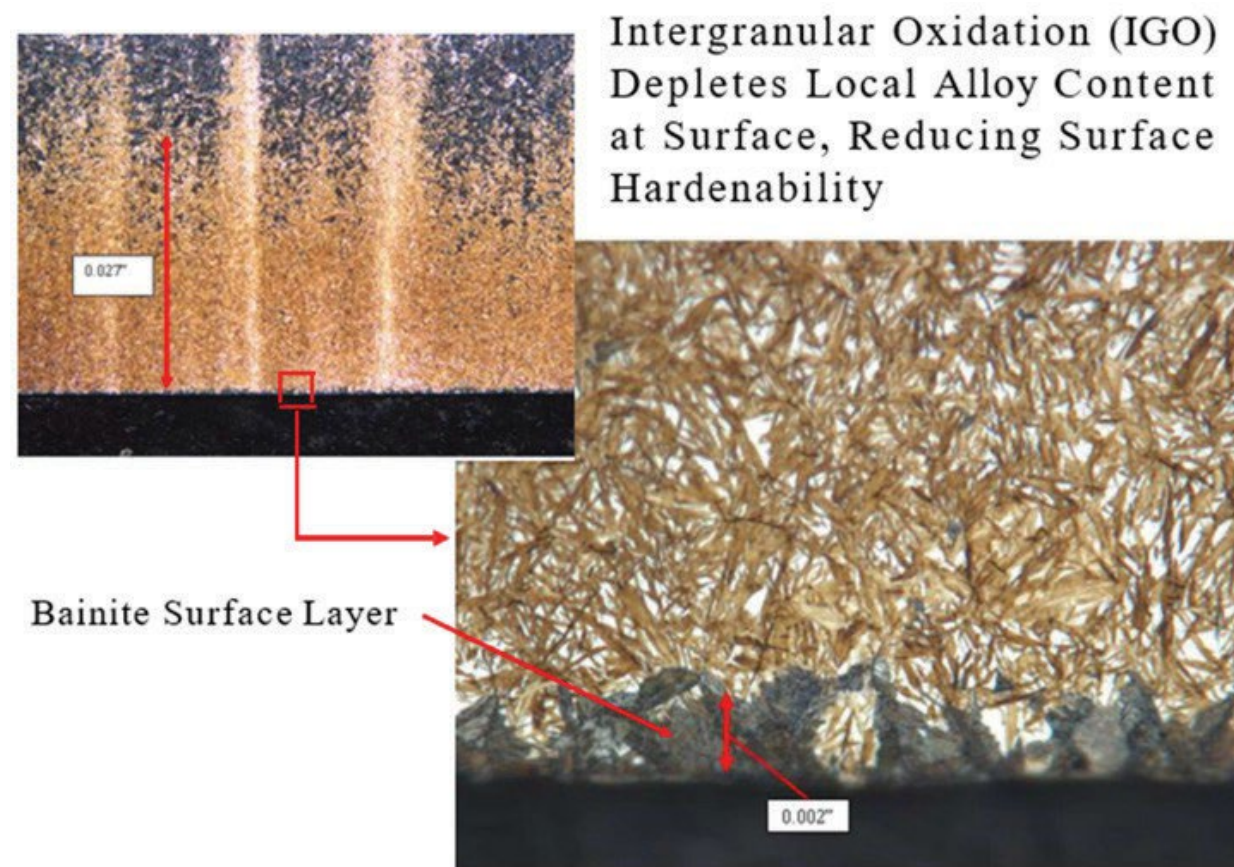
Occurs during extended holds at high temperatures without a controlled carbon atmosphere

At high temperatures, carbon diffuses inward and if no carbon is present in the atmosphere, the surface carbon content will be lowered

Creates a softer surface layer, reducing wear resistance

Also creates tensile stress on the surface resulting in the potential for spalling failure or premature in-service failure

Oxidation & Scale Formation



Oxidation can occur if a hot steel surface is exposed to oxygen

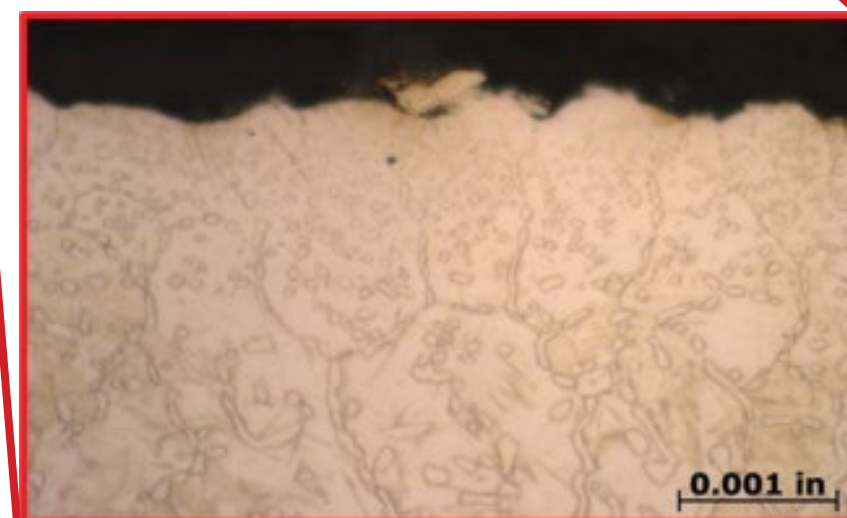
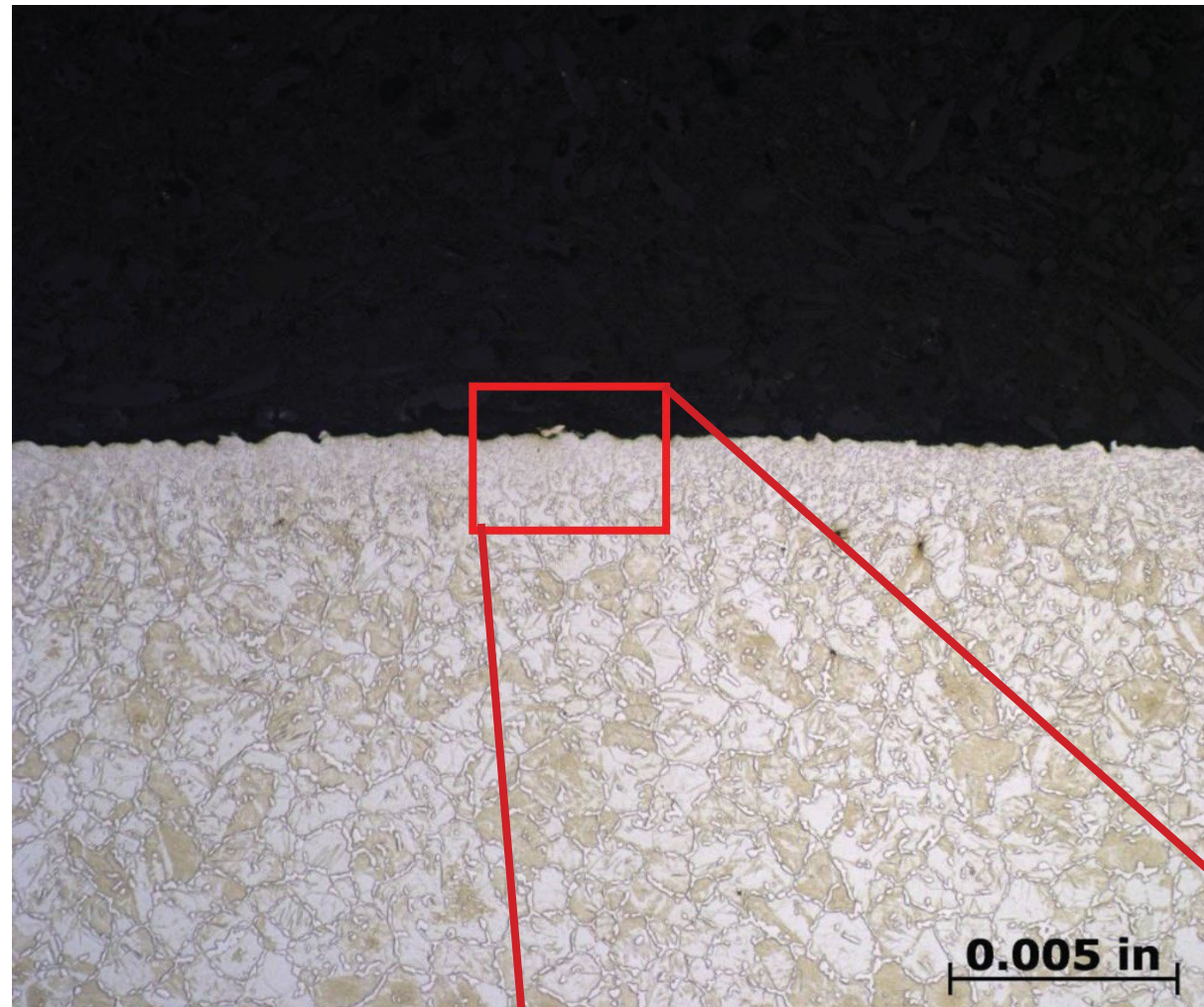
Iron oxide called scale is produced (black (Fe_3O_4), red (Fe_2O_3))

Creates a rough surface finish

Changes part dimensions and interferes with other manufacturing steps

Prevent with protective atmosphere or vacuum heat treat

Excessive Carbide Formation



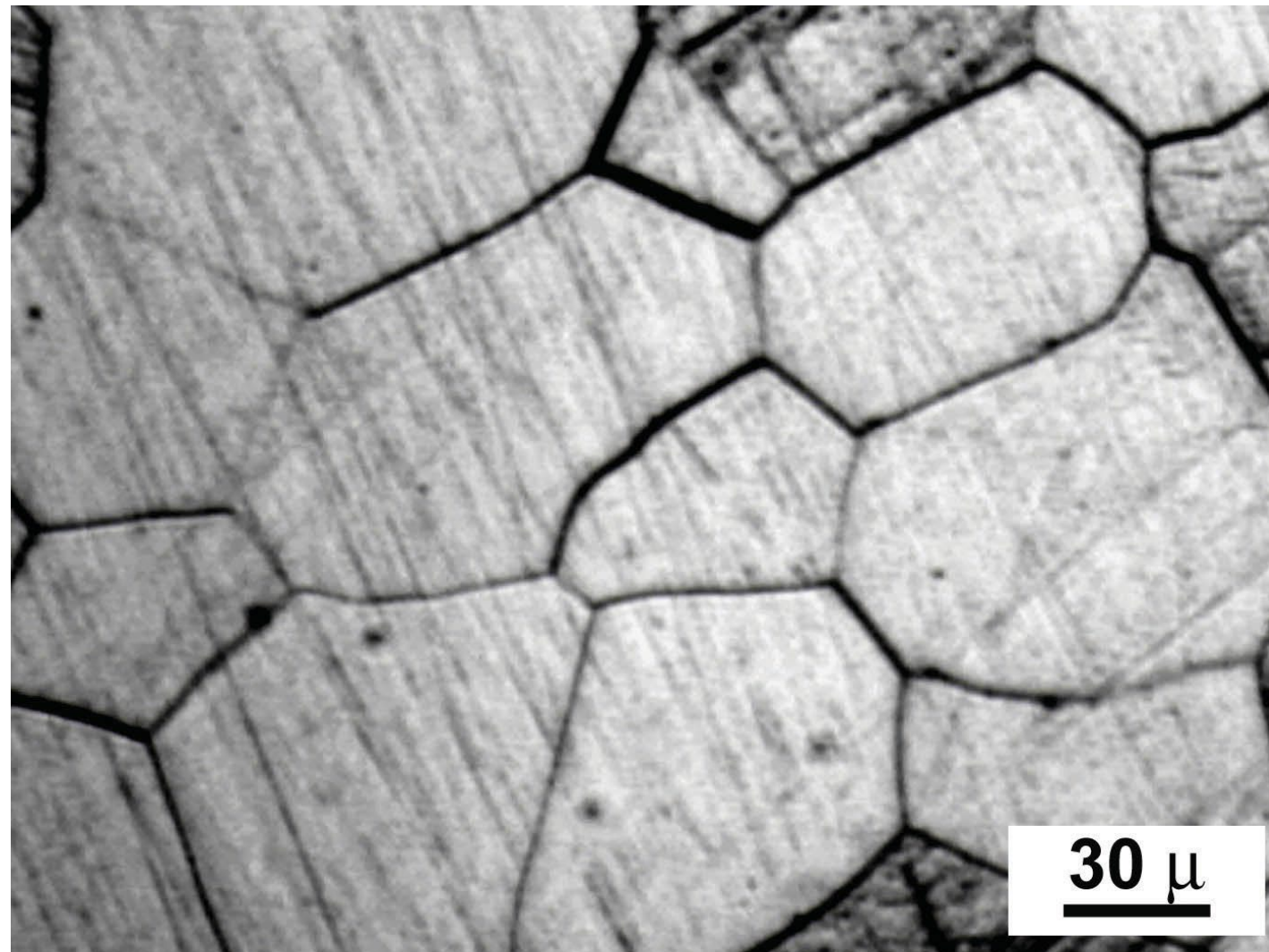
Carbides are hard carbon-containing compounds with iron or other alloying elements

Large, coarse carbides in the microstructure results in reduced fatigue resistance, reduced toughness, increased brittleness

Excessive carbides can form carbide networks where cracks may initiate or propagate

Carbide formation occurs when the carbon potential of steel exceeds the saturation point of the carbon in the austenitic microstructure

Grain Growth



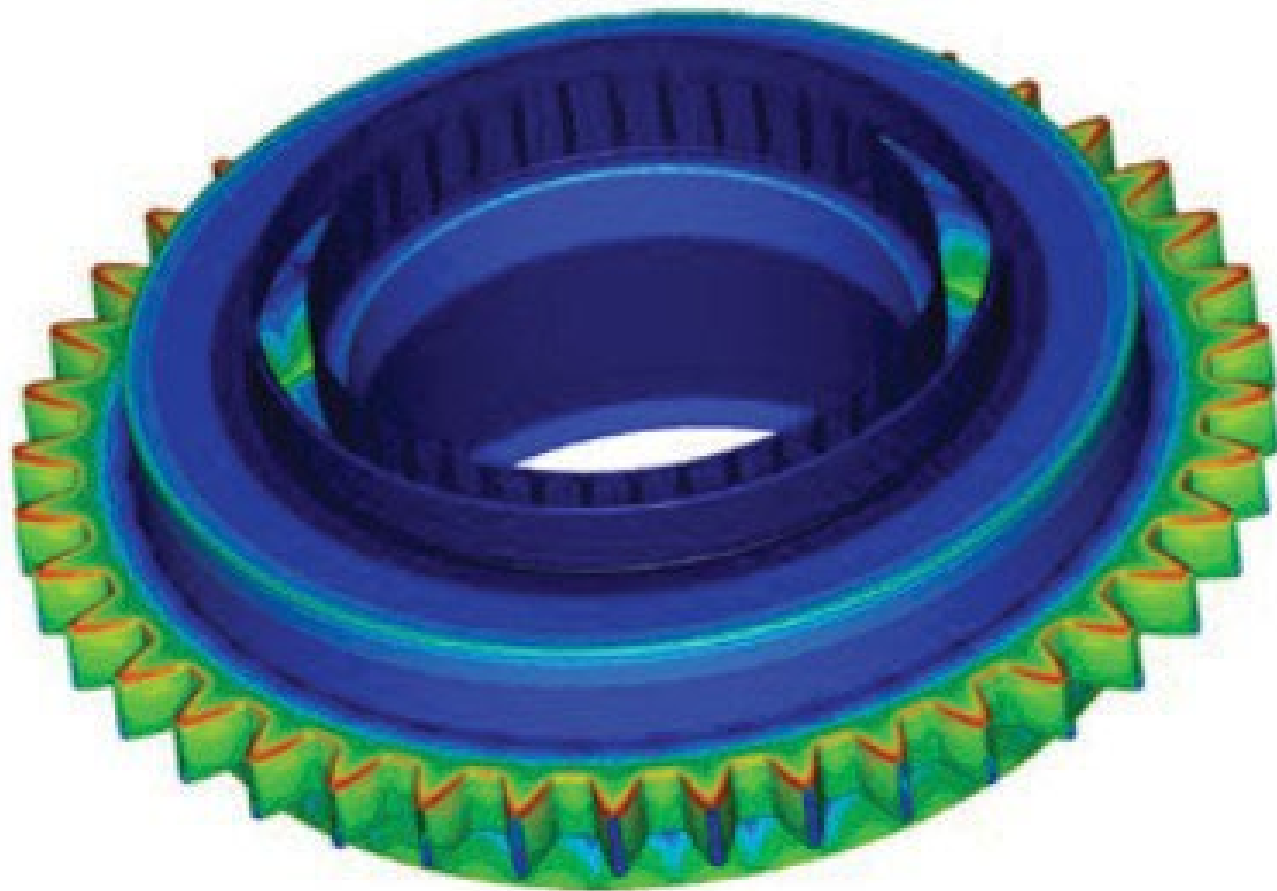
By Edward Pleshakov - Own work, CC BY 3.0, <https://commons.wikimedia.org/w/index.php?curid=3912586>

If the part is exposed to high temperatures for too long, the steel crystal grains can grow

Reduces toughness, lowers impact resistance, changes strength and fatigue behavior

Prevent by using the right austenitizing temperature and avoiding long soak times

Heat Treatment Process Modeling



Heat treatment process modeling uses mathematical and computer models to predict a part's response to heat treatment

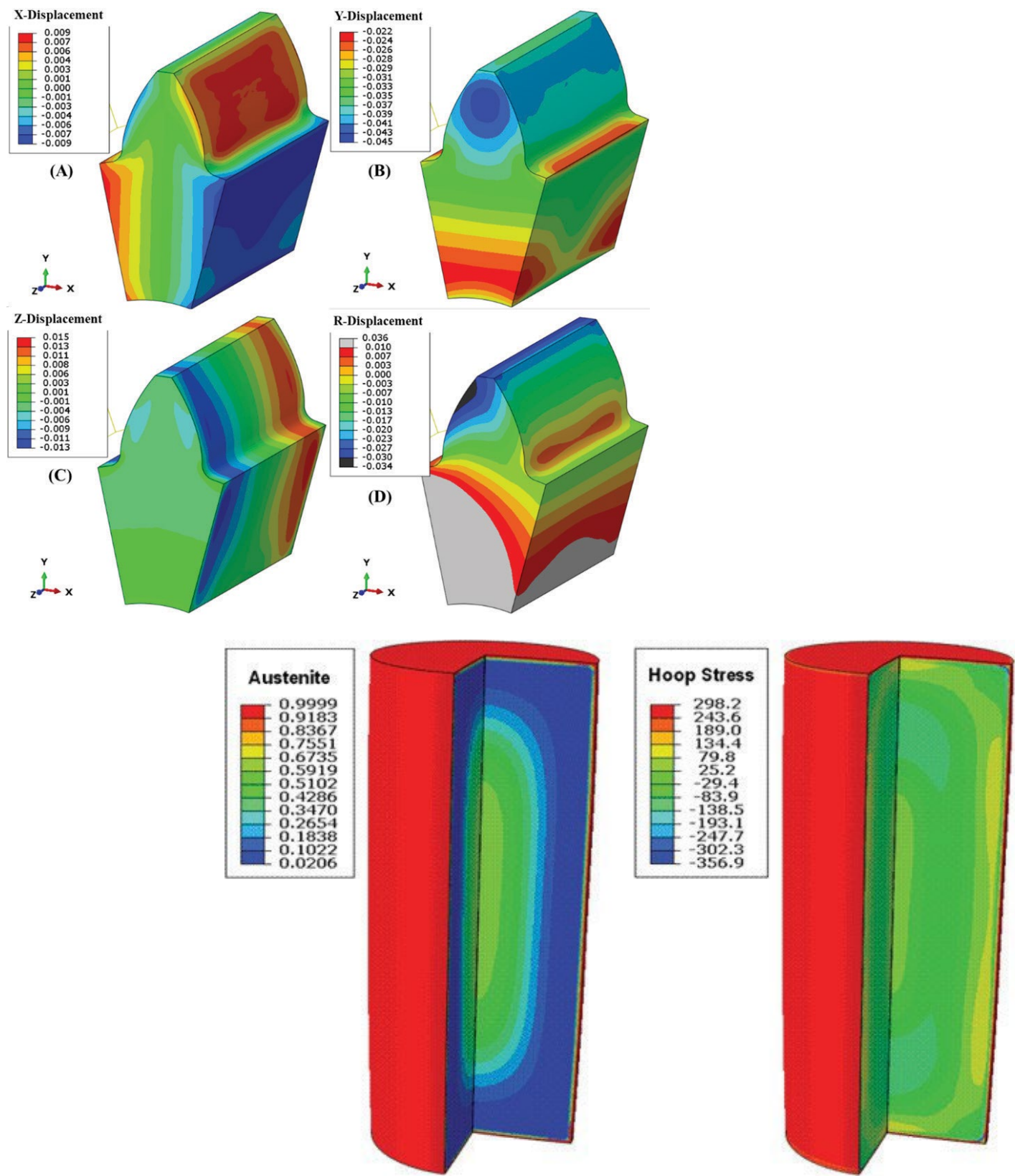
Modeling can be used to predict temperature, phase transformations, hardness, stresses, distortion, and other quantities in a heat treated part

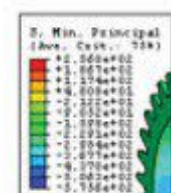
Why Model Heat Treatment?

Heat treatment simulation helps users gain a better understanding of their processes

Useful for process design and troubleshooting issues like distortion, quench cracking, and residual stress

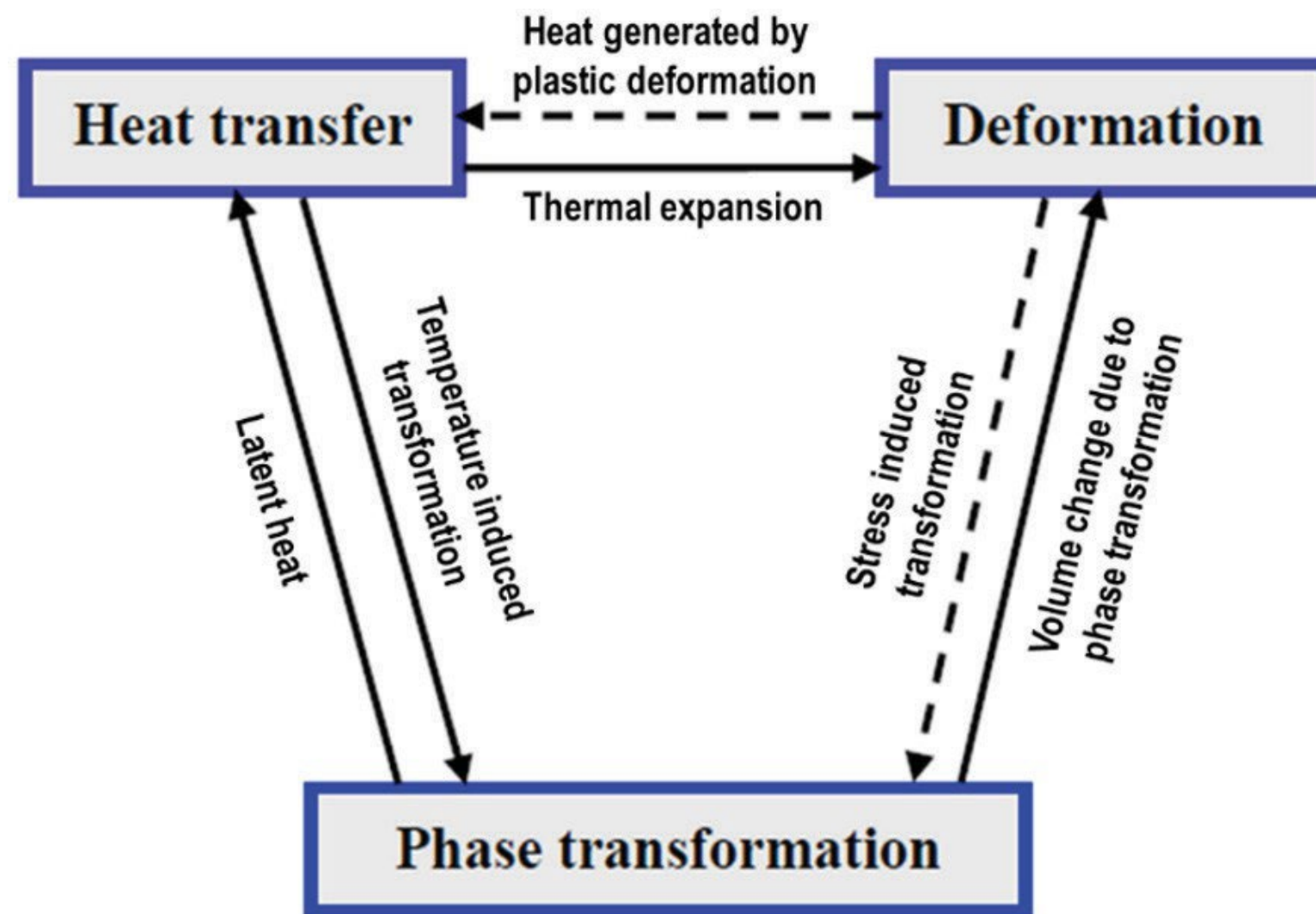
Modeling can be used to virtually test various process scenarios, reducing trial-and-error physical trials





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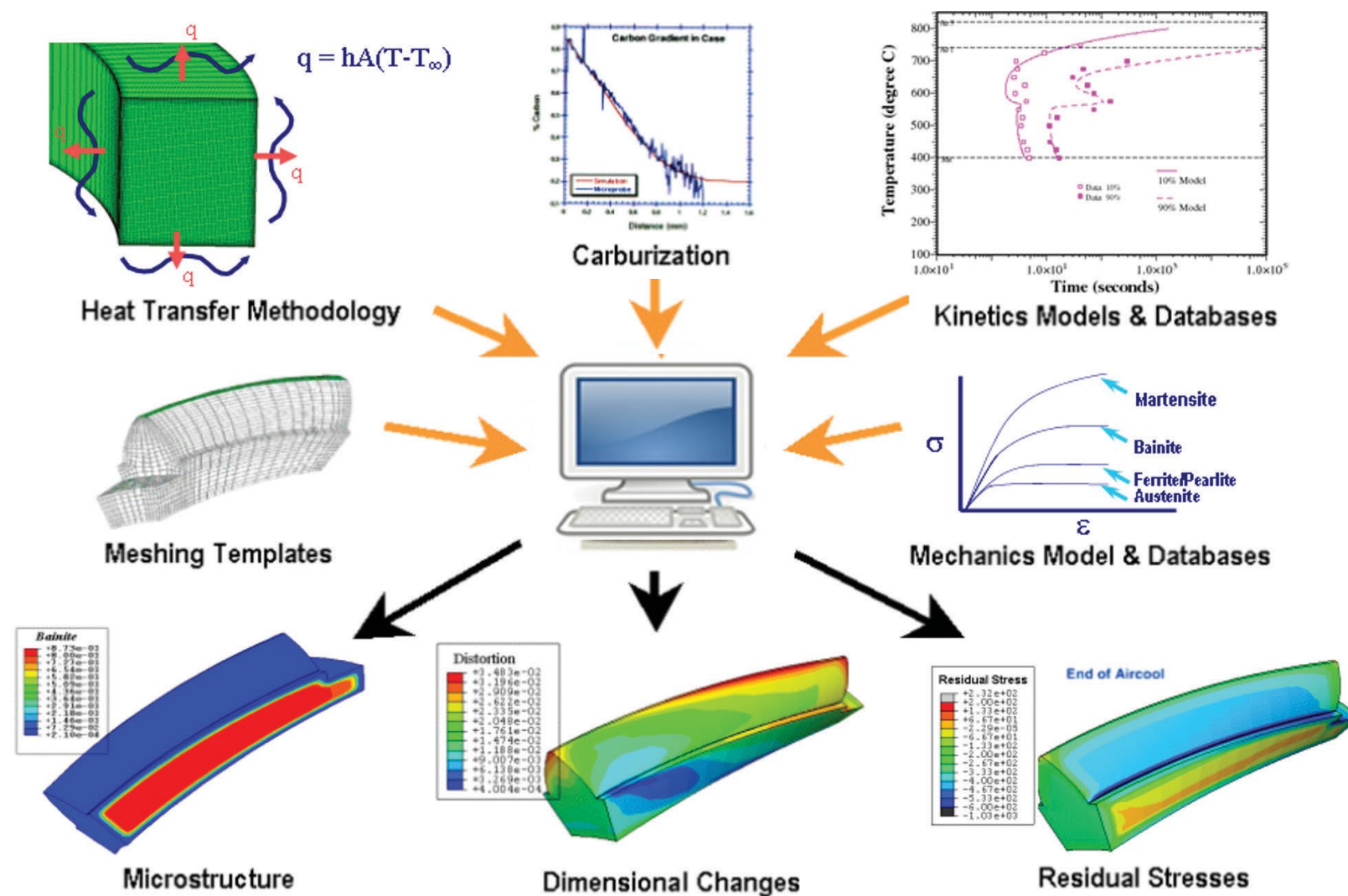
Heat Treat Modeling Requirements



Heat treat models simulate heat transfer, deformation, and phase transformations in a part during the process

Process is usually modeled with sequentially coupled thermal and mechanical models

Material model includes phase transformations, transformation-induced plasticity, tempering, carburizing, nitriding, etc.



Process modeled by specifying times, temperatures, and thermal boundary conditions like convective heat transfer coefficients to capture the heating and cooling behavior of process equipment

Material properties are defined over a wide range of temperatures and carbon levels

Model outputs contours or plots of predicted temperature, carbon/nitrogen content, microstructure volume fractions, hardness, distortion, and in-process and residual stress

Student Trial License



Students can get hands-on experience with the DANTE Student/Trial License

Several tutorials, examples, and videos are available in the DANTE ecosystem

Up to 10,000 elements with 10XX and 41XX steel

Download from our website

Contact Information

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