



**THE UNIVERSITY OF ZAMBIA
SCHOOL OF ENGINEERING
DEPARTMENT OF MECHANICAL
ENGINEERING**

**MEC 2309 – PROPERTIES OF ENGINEERING
MATERIALS I**

LECTURE 10

HEAT TREATMENT OF STEELS

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INTRODUCTION

- Machine components and structural members operate at extreme conditions of excessive mechanical loads, and high temperatures and pressure which induce stresses in the material.
- Similarly, metal working processes such as welding or cutting expose the material to some quantifiable amounts of heat which in turn induce thermal stresses in the material.

INTRODUCTION

- As materials engineers, we are interested in the methods of enhancing the properties of material in order for them to support and withstand the desired working conditions as well as restoring the material to its original condition.
- Heat treatment is one method employed for this activity.
- The process of heat treating is the method by which metals are heated and cooled in a series of specific operations that never allow the metal to reach the molten state.

INTRODUCTION

- The purpose of heat treating is to make a metal more useful by changing or restoring its mechanical properties.
- Through heat treatment, we can make a metal harder, stronger, and more resistant to impact.
- Also, heat treating can make a metal softer and more ductile.
- The one disadvantage is that no heat-treating procedure can produce all of these characteristics in one operation.

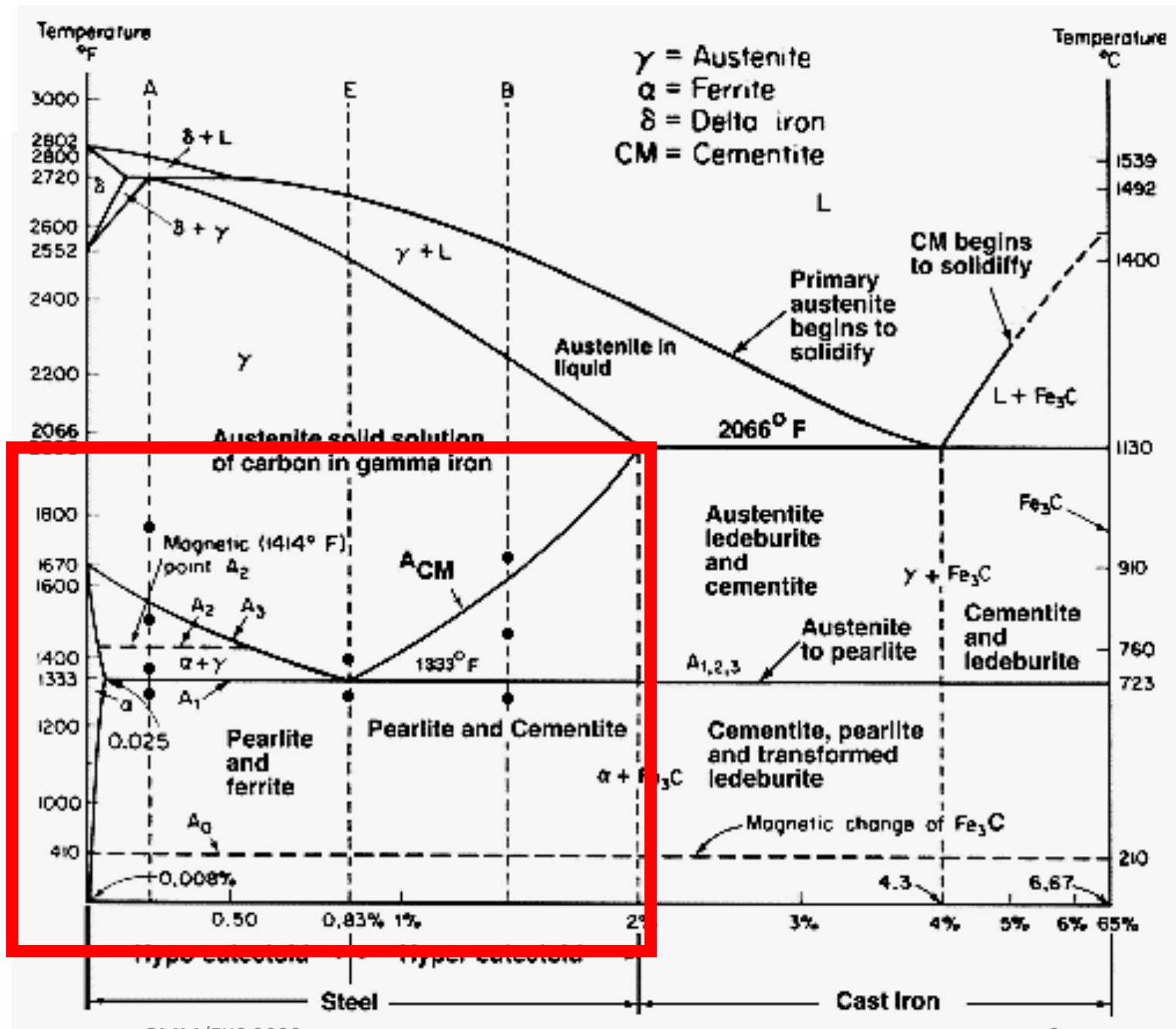
INTRODUCTION

- Some properties are improved at the expense of others. E.G. Hardening a metal may make it brittle or trying to soften it might make it weak.
- Heat treatment, therefore, involves trade-offs in the final properties that a material will have.
- The aim of the materials engineer is to get the optimum properties possible for a given application using a given material.

INTRODUCTION

- The development of a set of desirable mechanical characteristics for a material often results from a phase transformation that is wrought by the selected heat treatment.
- For iron–carbon alloys, the development of microstructural elements other than pearlite are possible.
- These microstructures, their mechanical properties, and their structure-property correlations and how they are achieved through heat treatment.

INTRODUCTION



Region of interest!!



CLASSIFICATIONS OF STEELS

Low-Carbon Steels

- Of all the different steels, those produced in the greatest quantities fall within the low-carbon classification.
- These generally contain less than about 0.25 wt% C and are unresponsive to heat treatments intended to form martensite;
- Strengthening is accomplished by cold work. Microstructures consist of ferrite and pearlite constituents.
- These alloys are relatively soft and weak but have outstanding ductility and toughness; in addition, they are machinable, weldable, and, of all steels, are the least expensive to produce. Typical applications include auto- mobile body components, structural members



CLASSIFICATIONS OF STEELS

High-Carbon Steels

- The high-carbon steels, normally having carbon contents between 0.60 and 1.4 wt%, are the hardest, strongest, and least ductile of the carbon steels.
- They are almost always used in a hardened and tempered condition and, as such, are especially wear resistant and capable of holding a sharp cutting edge. These steels are utilized as cutting tools and dies for forming and shaping materials, as well as in knives, razors, hacksaw blades, springs, and high-strength wire.



GENERAL HEAT TREATMENT PROCESS

- **Stage 1 – heating** the metal slowly to ensure a uniform temperature.
- **Stage 2 – soaking** (holding) the metal at a given or required temperature for a given time.
- **Stage 3 – cooling** the metal to room temperature

Successful heat treatment requires close control over all factors affecting the heating and cooling of a metal.

STAGE 1: HEATING

- The primary objective in the heating stage is to maintain uniform temperatures. If uneven heating occurs, one section of a part can expand faster than another and result in distortion or cracking.
- Uniform temperatures are attained by slow heating. The heating rate of a part depends on several factors. One important factor is the heat conductivity of the metal.
- A metal with a high-heat conductivity heats at a faster rate than one with a low conductivity.

STAGE 2: SOAKING

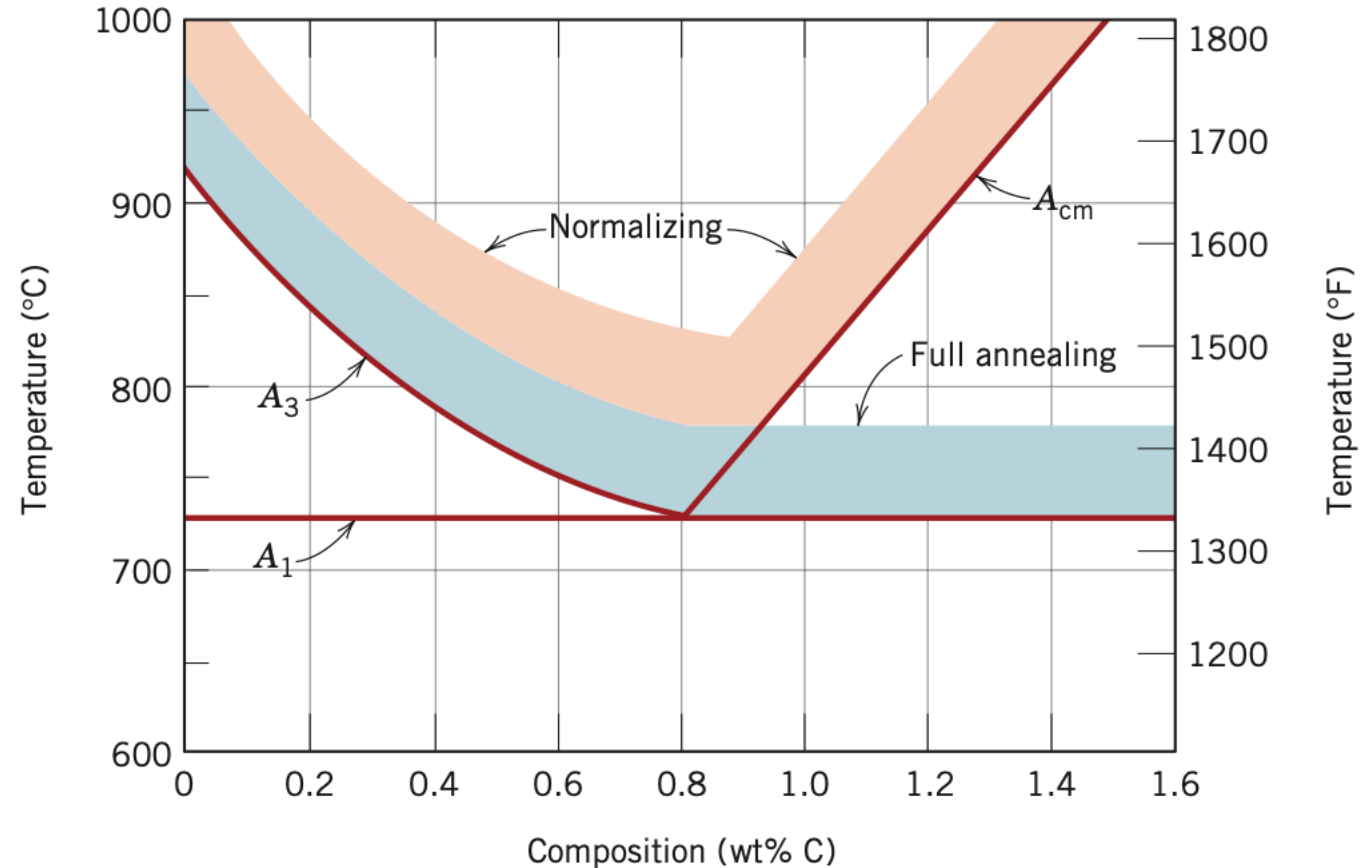
- After the metal is heated to the proper temperature, it is held at that temperature until the desired internal structural changes take place.
- This process is called soaking. The length of time held at the proper temperature is called the soaking period.
- Soaking period depends on the chemical analysis of the metal and the mass of the part.

STAGE 3: COOLING

- After a metal has been soaked, it must be returned to room temperature to complete the heat-treating process.
- To cool the metal, it can be placed in direct contact with a cooling medium composed of a gas, liquid, solid, or combination of these.
- The rate at which the metal is cooled depends on the metal and the properties desired.
- The rate of cooling also depends on the medium; therefore, the choice of a cooling medium has an important influence on the properties desired.

LOWER AND UPPER CRITICAL TEMPERATURES

- The horizontal line at the eutectoid temperature, conventionally labeled **A1**, is termed the **lower critical temperature**, below which, under equilibrium conditions, all austenite will have transformed into ferrite and cementite phases.
- The phase boundaries denoted as **A3** and **A_{cm}** represent the **upper critical temperature lines** for hypoeutectoid and hypereutectoid steels, respectively. For temperatures and compositions above these boundaries, only the austenite phase will prevail.



COMMON METHODS OF HEAT TREATING METALS

- The usual methods of heat-treating ferrous metals (metals with iron) are **annealing**, **normalising**, **hardening**, and **tempering**.
- Most non-ferrous metals can be annealed, but never tempered, normalised, or case-hardened.
- All these types of heat-treating processes are similar because they all involve the heating and cooling of metals.
- They differ in the heating temperatures and the cooling rates used and the final results.

TYPES OF HEAT TREATMENT

- We shall now look at these four basic types of heat treatment used today, namely: **annealing, normalising, hardening, and tempering.**
- We shall look at the techniques used in each process and how they relate to metal working
- Away we go.....!!!

HEAT-TREATING:ANNEALING

The term annealing refers to a heat treatment in which a material is exposed to an elevated temperature for an extended time period and then slowly cooled. Annealing is carried out to:

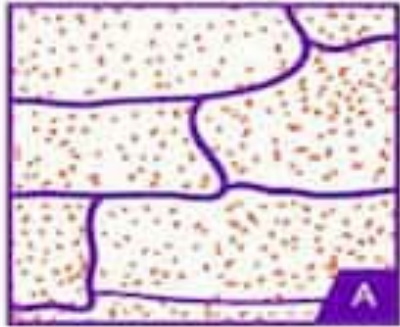
- 1) relieve stresses;
- 2) increase softness, ductility, and toughness; and/or
- 3) produce a specific microstructure or remove gases.

A variety of annealing heat treatments are possible; they are characterized by the changes that are induced, which many times are microstructural and are responsible for the alteration of the mechanical properties.

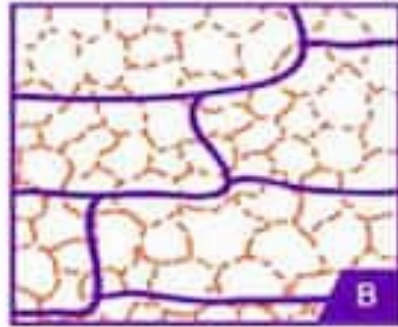
HEAT-TREATING:ANNEALING

- Annealing improves the formability of a material. Hard, brittle materials can be difficult to bend or press without breaking the material. Annealing eliminates this risk.
- Annealing can also improve machinability. A material that is extremely brittle can cause excessive tool wear. By reducing the hardness of a material by annealing, the wear and tear of the tool used can be reduced.
- The annealing removes residual stresses. Residual stresses can cause cracks and other mechanical complications, and it is often best to eliminate them whenever possible.

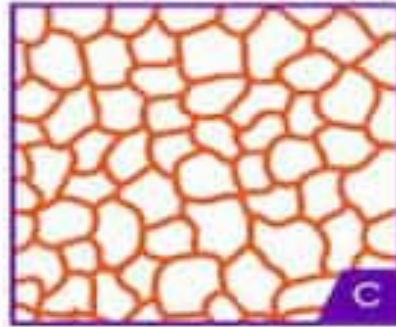
What is Annealing??



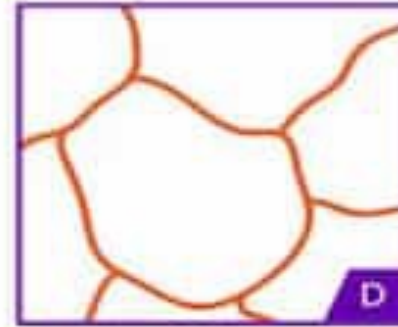
Initial cold state



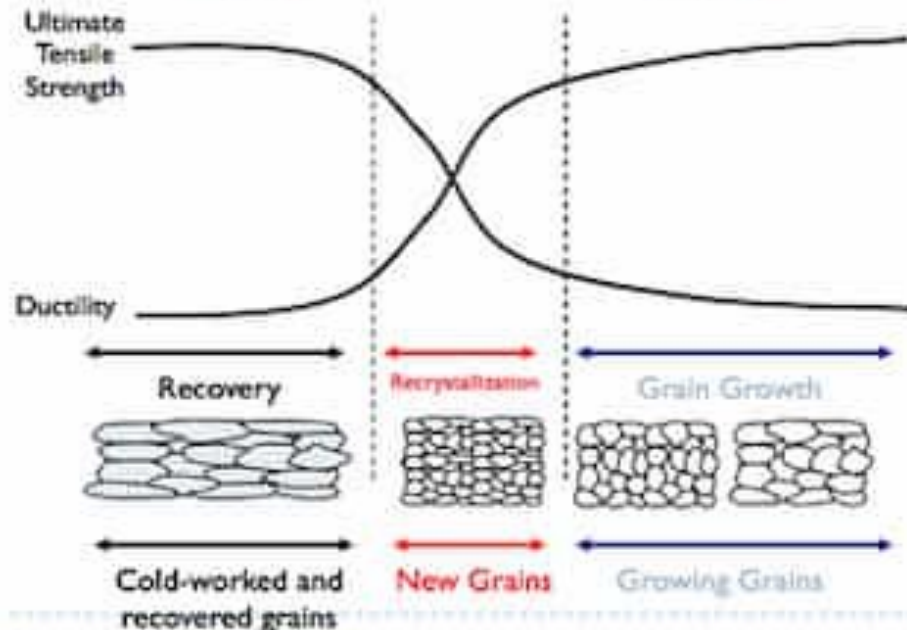
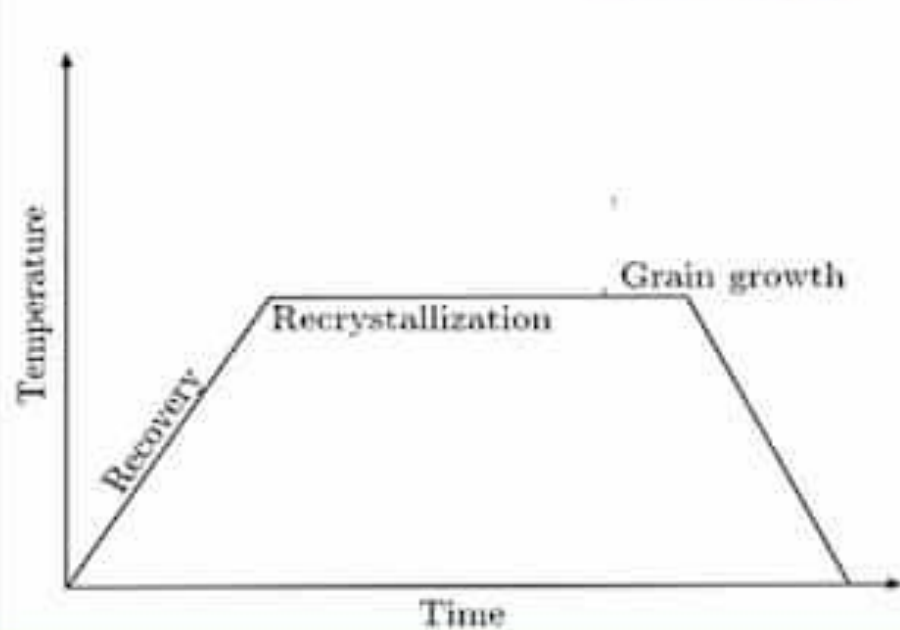
Heating; high stress areas dissipate



Recrystallization forms



Recrystallization forms



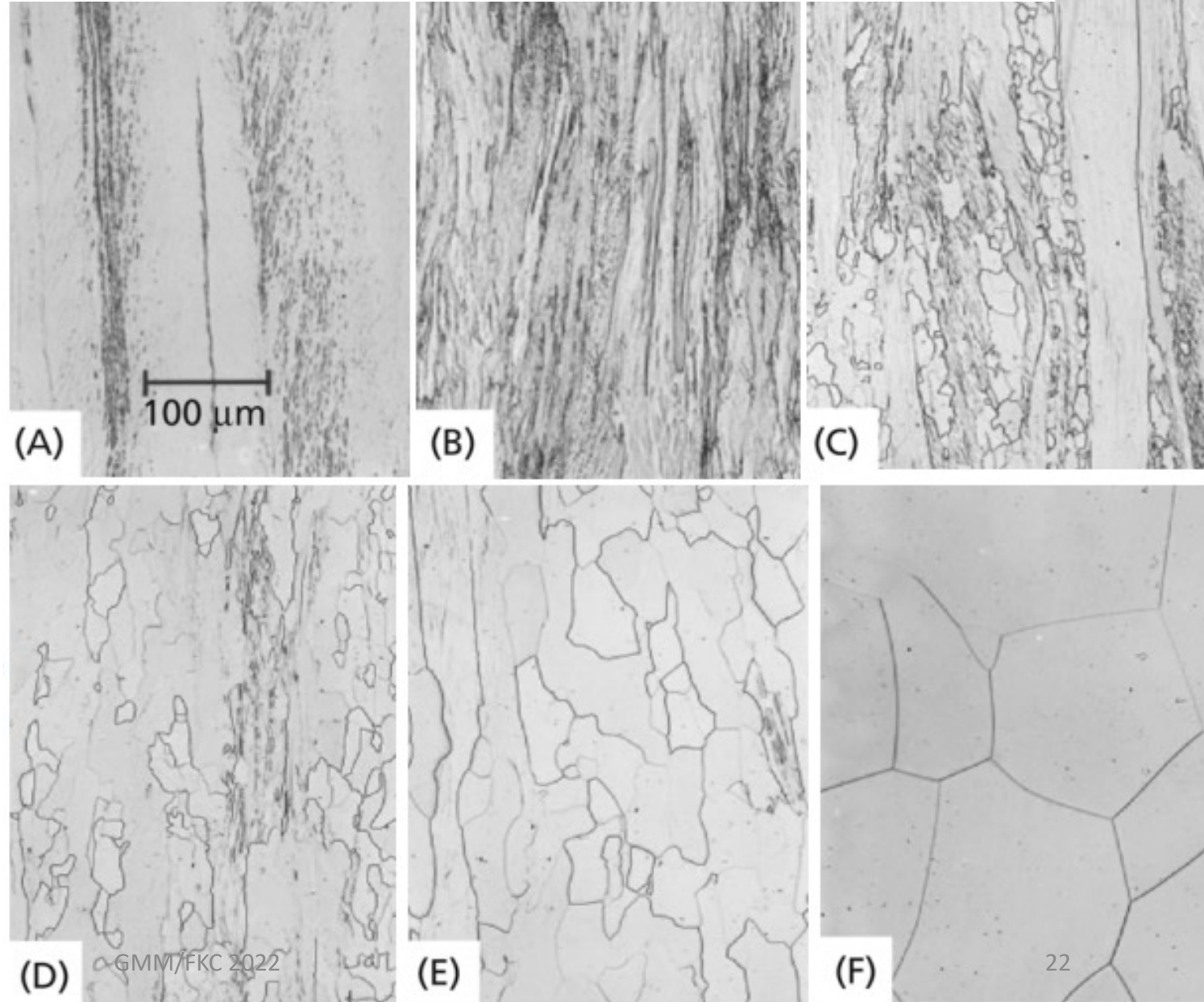
A) Full Annealing

- A heat treatment known as full annealing is often utilized **in low and medium carbon steels** that will be machined or will experience extensive plastic deformation during a forming operation.
- In general, the alloy is treated by heating to a temperature of **about 50°C above the A3 line** (to form austenite) for compositions less than the eutectoid, or, for compositions in excess of the eutectoid, **50°C above the A1 line** (to form austenite and Fe₃C phases).
- The alloy is then furnace cooled; that is, the heat-treating furnace is turned off and both furnace and steel cool to room temperature at the same rate, which takes several hours.
- The microstructural product of this anneal is coarse pearlite (in addition to any proeutectoid phase) that is relatively soft and ductile.
- The full-anneal cooling procedure is time consuming; however, a microstructure having small grains and a uniform grain structure results.

A) Full Annealing

Optical view of microstructure of deformed iron at different annealing temperatures;

- (A) as cold rolled,
- (B) annealed at 300 °C,
- (C) annealed at 370 °C,
- (D) annealed at 410 °C,
- (E) annealed at 460 °C, and
- (F) annealed at 650 °C.



B) Process Annealing

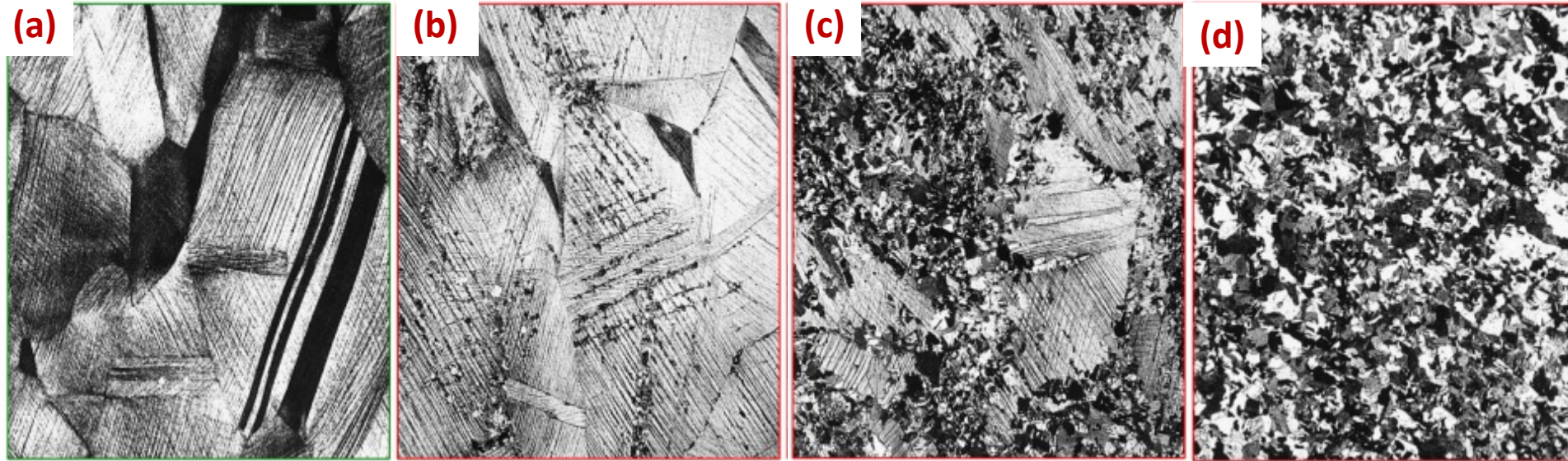
- Process annealing, frequently termed as stress-relief annealing, is usually applied to cold-worked low carbon steels (up to about 0.25% of carbon).
- Process annealing is a heat treatment that is used to negate the effects of cold work—that is, to soften and increase the ductility of a previously strain-hardened metal.
- It is commonly utilized during fabrication procedures that require extensive plastic deformation, to allow a continuation of deformation without fracture or excessive

B) Process Annealing

- This type of anneal will cause recrystallisation and softening of the cold-worked ferrite grains, but usually will not affect the relatively small amounts of cold-worked pearlite.
- The steel is usually heated close to, but below, the critical temperature.
- If the steel is not to be further cold-worked, but relief of internal stresses is desired, a lower range of temperature will suffice but the rate of cooling is immaterial.

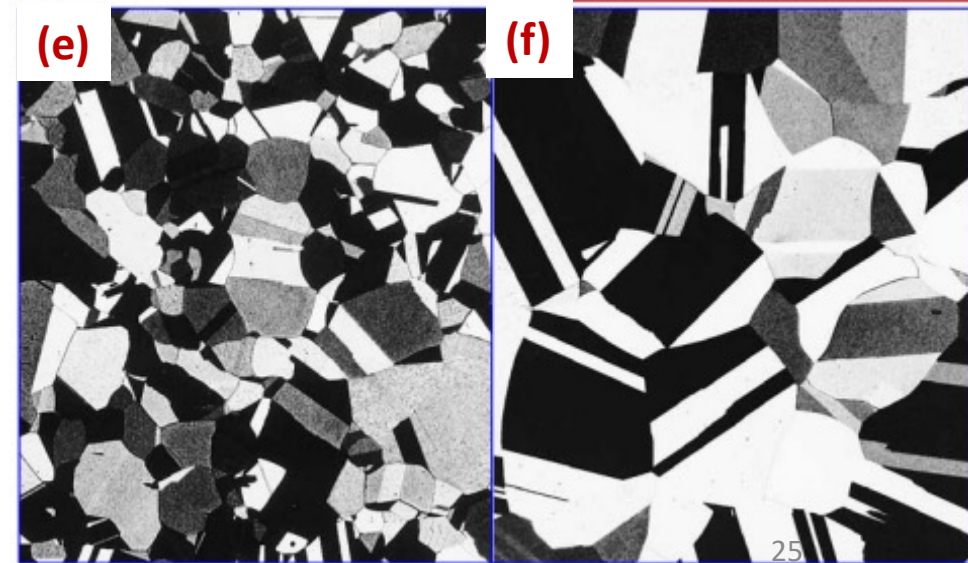
B) Process Annealing

Recrystallisation



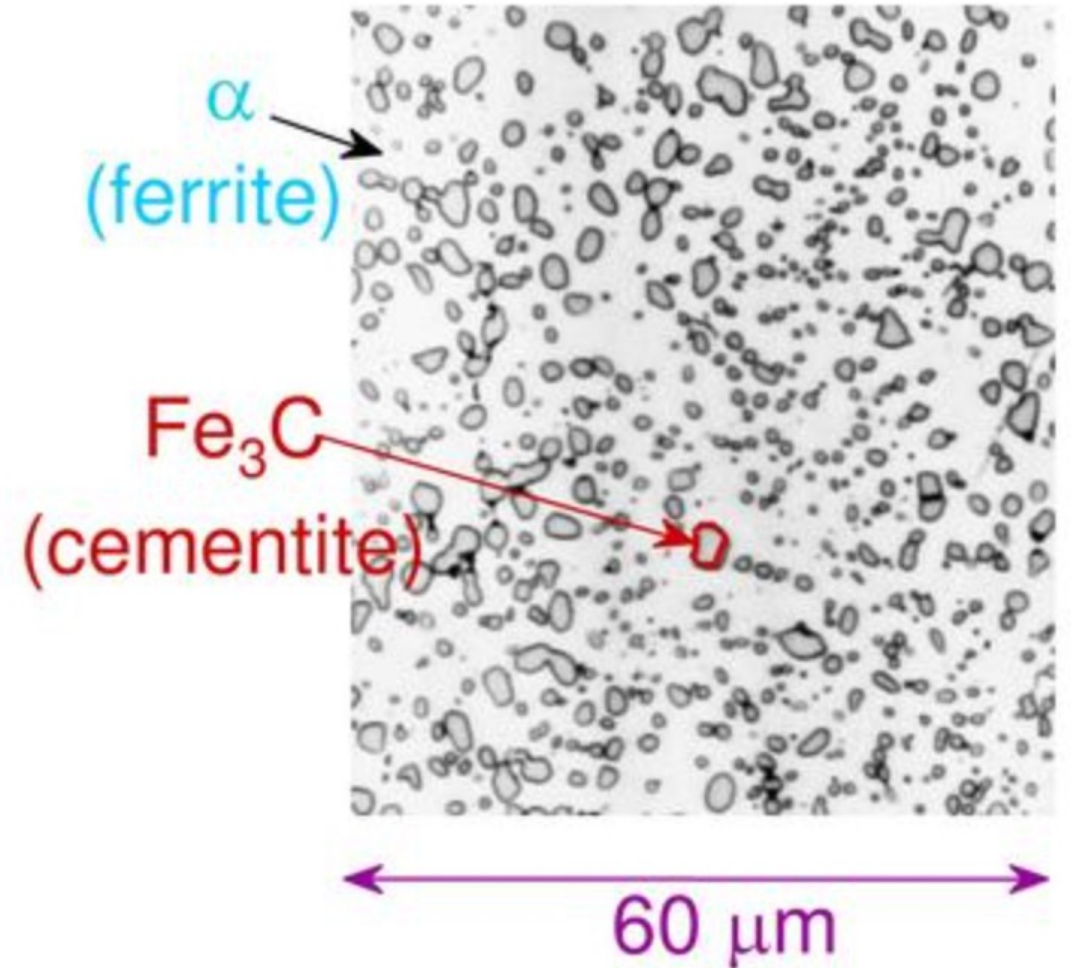
Photomicrographs showing several stages of the recrystallisation and grain growth of brass.

- (a) Cold-worked (33% CW) grain structure.
- (b) Initial stage of recrystallisation after heating 3s at 580 °C; the very small grains are those that have recrystallised.
- (c) Partial replacement of cold-worked grains by recrystallised ones (4s at 580 °C).
- (d) Complete recrystallisation (8s at 580 °C).
- (e) Grain growth after 15 min at 580 °C.
- (f) Grain growth after 10 min at 700 °C.



C) Spheroidising

- If a steel alloy having either pearlitic or bainitic microstructures is heated to, and left at, a temperature below the eutectoid for a sufficiently long period of time— for example, at about 700°C for between 18 and 24 hours **yet another microstructure will form**. It is called **Spheroidite**.
- Instead of the alternating ferrite and cementite lamellae (pearlite), or the microstructure observed for bainite, the Fe_3C phase appears as spherelike particles embedded in a continuous α (ferrite) phase matrix.



C) Spheroidising

- Medium- and high-carbon steels having a microstructure containing even coarse pearlite may still be too hard to conveniently machine or plastically deform. These steels, and in fact any steel, may be heat-treated or annealed to develop the spheroidite structure.
- Spheroidized steels have a maximum softness and ductility and are easily machined or deformed. The spheroidizing heat treatment results in the coalescence of the Fe_3C to form the spheroid particles, can take place by several methods.

C) Spheroidising

- This treatment is usually applied to the high carbon steels (0.60% of carbon and higher).
- The purpose of the treatment is to improve machinability and it is also used to condition high-carbon steel for cold-drawing into wire.

C) Spheroidising

Spheroidising can be accomplished using the following three methods:

1. Heating the alloy at a temperature just below the eutectoid [line A1 in , or at about 700°C in the austenite-Fe₃C region of the phase diagram. If the precursor microstructure contains pearlite, spheroidizing times will ordinarily range between 15 and 25 h.
2. Heating to a temperature just above the eutectoid temperature, and then either cooling very slowly in the furnace, or holding at a temperature just below the eutectoid temperature.
3. Heating and cooling alternately within about ±50°C of the A1 line of Figure 11.10.
 - To some degree, the rate at which spheroidite forms depends on prior microstructure. For example, it is slowest for pearlite, and the finer the pearlite, the more rapid the rate. Also, prior cold work increases the spheroidizing reaction rate. The final step, however, should consist of holding at a temperature just below the critical as the rate of cooling is immaterial after slowly cooling to about 540 °C.

HEAT-TREATING:NORMALISING

- Normalising is a process used to refine the grains (i.e., to decrease the average grain size) and produce a more uniform and desirable size distribution; fine-grained pearlitic steels are tougher than coarse grained ones.
- The steel is heated to a temperature above the critical line and then cooled in still air.
- The most common reason for the normalising process is to adjust mechanical properties to suit the service conditions.
- The other purpose of the normalising is to relieve the internal stresses; to refine the grain structure, and to improve the machinability.

HEAT-TREATING:NORMALISING

- Normalizing is accomplished by heating at least 55°C (above the upper critical temperature—that is, above A_3 for compositions less than the eutectoid (0.83 wt% C), and above A_{cm} for compositions greater than the eutectoid
- After sufficient time has been allowed for the alloy to completely transform to austenite—a procedure termed austenitizing—the treatment is terminated by cooling in air.
- The usual normalising temperature ranges from 815°C to 980°C , depending on the steel involved.

HEAT-TREATING:NORMALISING

- Holding at this temperature for a shorter time to prevent grain growth and finally, cooling in air.
- The time allowed should be sufficient so that the temperature is equalised throughout the section, for complete transformation to austenite, i.e. austenitising of the steel.
- After austenising, the alloy is air-cooled to a temperature substantially below the transformation range.
- The air-cooling avoids excessive proeutectoid segregation. The cooling rate is usually in the range of 500 to 1000 °C/h.

HEAT-TREATING:NORMALISING

- The structure produced by normalising is similar to that of annealing. But air cooling is faster than furnace cooling. Thus the normalised steels possess finer grains than annealed steels.
- The normalised structure of low-alloy steel consists of sorbite (fine pearlite) and fine ferrite.
- The increased rate of cooling in normalising results in high hardness and low ductility than annealed steel, i.e. machinability will be easy.

HEAT-TREATING:NORMALISING

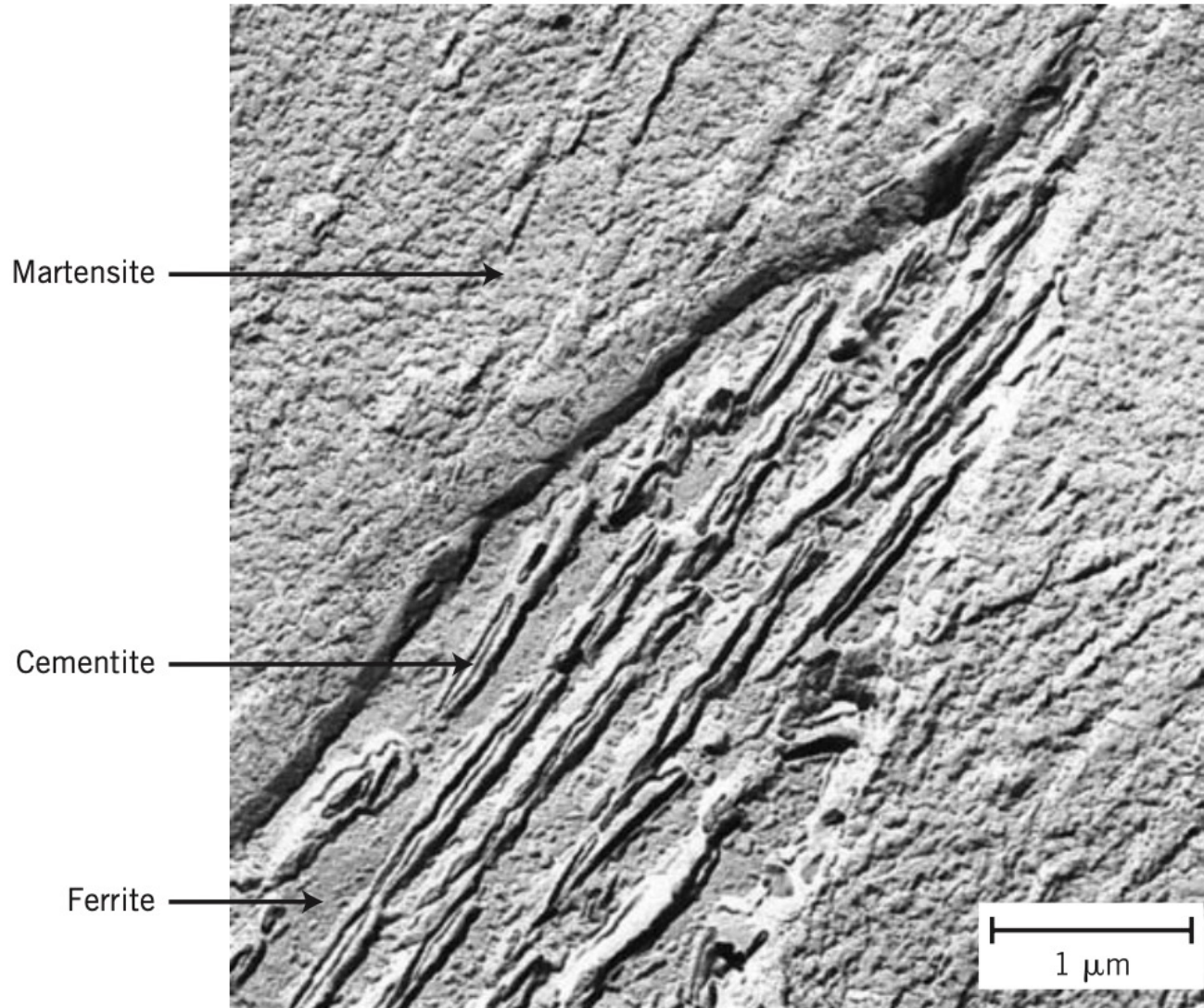
- Normalising is mainly to obliterate the effects of any previous heat treatment (including the coarse grained structure sometimes resulting from high forging temperatures) or cold-working and to ensure a homogeneous austenite on reheating for hardening or full annealing.
- It removes the internal stresses induced by heat treating, welding, casting, forging, forming, or machining.
- Normalised steels are harder and stronger than annealed steels

HEAT-TREATING:NORMALISING

- The final microstructure consists of fine pearlite and an absence of massive pro-eutectoid ferrite. Normalising is commonly specified for plates of pressure vessel quality above 1½ inch in thickness.

HEAT-TREATING:NORMALISING

Transmission electron micrograph showing the structure of bainite. A grain of bainite passes from lower left to upper right corners; it consists of elongated and needle-shaped particles of Fe_3C within a ferrite matrix. The phase surrounding the bainite is martensite. (Reproduced with permission from Metals Handbook, 8th edition, Vol. 8, Metallography, Structures and Phase Diagrams, American Society for Metals, Materials Park, OH, 1973.)



HEAT-TREATING:HARDENING

- Steels can be hardened by the simple expedient of heating to above the transformation temperature, holding long enough to insure the attainment of uniform temperature and solution of carbon in the austenite, and then cooling rapidly (quenching).
- The hardening process allows the austenite to transform to martensite. Most alloys require rapid cooling (quenching) for hardening but a few can be air-cooled with the same results.

HEAT-TREATING:HARDENING

- Hardening increases the hardness and strength of the steel, but makes it less ductile.
- Generally, the harder the alloy, the more brittle it becomes.
- To harden ferrous metals, the metal is rapidly cooled after thoroughly soaking it at a temperature slightly above its upper critical point.

HEAT-TREATING:HARDENING

- In plain carbon steel, the maximum hardness obtained by heat treatment depends almost entirely on the carbon content of the steel.
- As the carbon content increases, the hardening ability of the steel increases;
- However, this capability of hardening with an increase in carbon content continues only to a certain point.
- In practice, 0.80 percent carbon is required for maximum hardness.

CASE HARDENING

- **Case hardening** is a process of hardening a ferrous alloy so that the surface layer or case is made substantially harder than the interior or core.
- The chemical composition of the surface layer is altered during the treatment by the addition of carbon, nitrogen, or both.
- The most frequently used case-hardening processes are carburising, cyaniding, and nitriding.

A) Carburising

- Carburising is a process that introduces carbon into solid ferrous alloy by heating the metal in contact with a carbonaceous material to a temperature above the transformation temperature of the steel and holding at that temperature.
- The depth of penetration of carbon is dependent on temperature, time at temperature, and the composition of the carburising agent. After carburising, the steel will have a high-carbon case graduating into the low-carbon core.

B) Cyaniding

- Cyaniding process involves the introduction of both carbon and nitrogen into the surface layers of the steel.
- Steels to be cyanided normally are heated in a molten bath of cyanide-carbonate-chloride salts (usually containing 30 to 95% of sodium cyanide) and then quenched in brine, water, or mineral oil.
- Steels can be cyanided also by heating to the proper temperature and dipping in a powdered cyanide mixture or sprinkling the powder on the steel, followed by quenching.

C) Nitriding

- The nitriding process involves the action of introducing the steel in a nitrogenous medium, usually ammonia gas, at a temperature of about 500 to 540 °C, whereby a very hard surface is obtained.
- The surface-hardening effect is due to the absorption of nitrogen and subsequent heat treatment of the steel is unnecessary.

HEAT-TREATING: TEMPERING

- After the hardening treatment is applied, steel is often harder than needed and is too brittle for most practical uses.
- Also, severe internal stresses are set up during the rapid cooling from the hardening temperature.
- To relieve the internal stresses and reduce brittleness, the steel is tempered after it is hardened.

HEAT-TREATING: TEMPERING

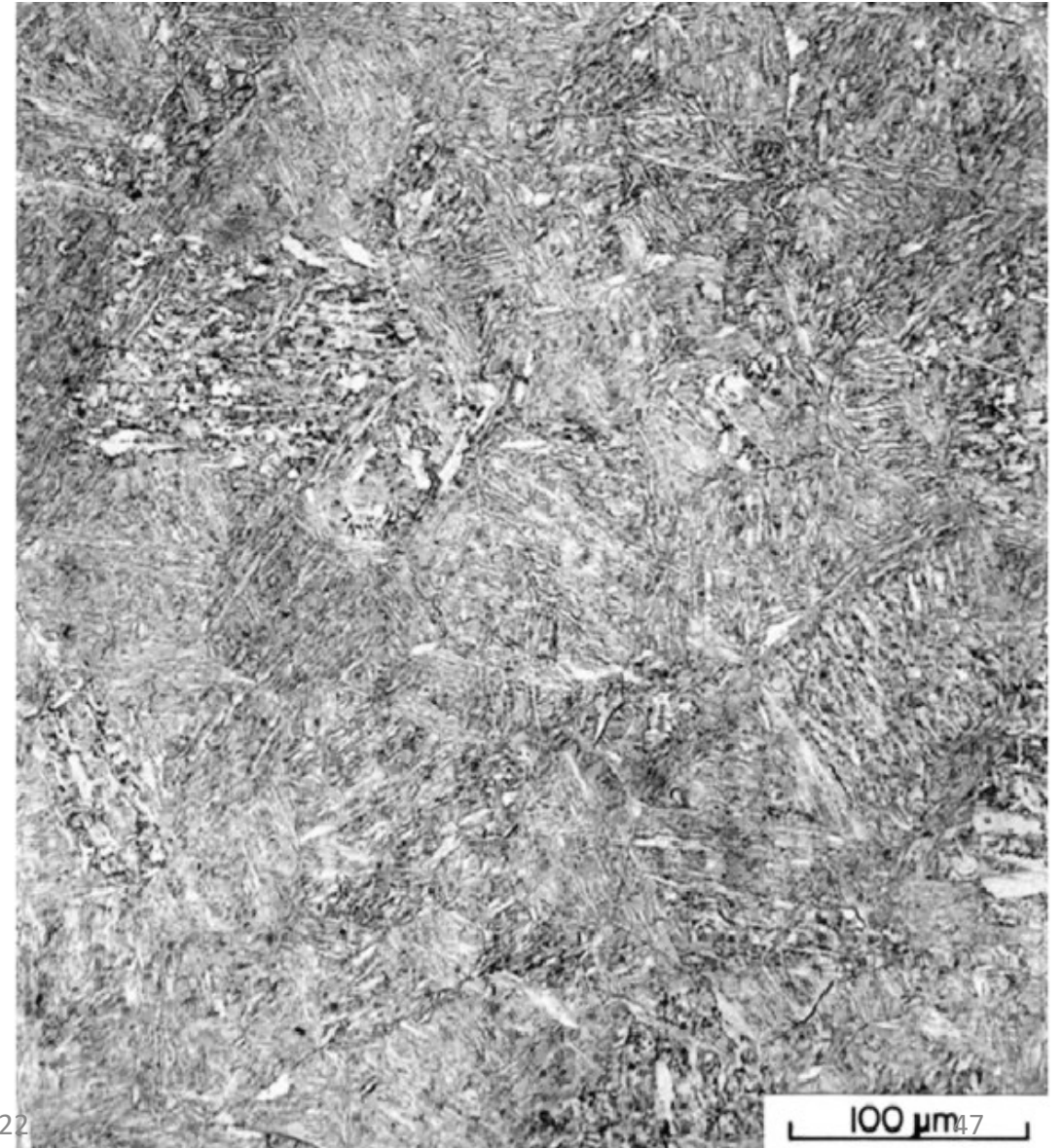
- Tempering (sometimes called drawing) is the process of reheating hardened (martensitic) or normalised steels to some temperature below the lower critical value before cooling.
- Tempering consists of heating the steel to a specific temperature (below its hardening temperature), holding it at that temperature for the required length of time, and then cooling it, usually in still air.

HEAT-TREATING: TEMPERING

- During tempering process, martensite in hardened steel is gradually changed into a structure consisting of spheroids of cementite in a matrix of ferrite.
- These changes are accompanied by a decreasing hardness and increasing toughness.

HEAT-TREATING: TEMPERING

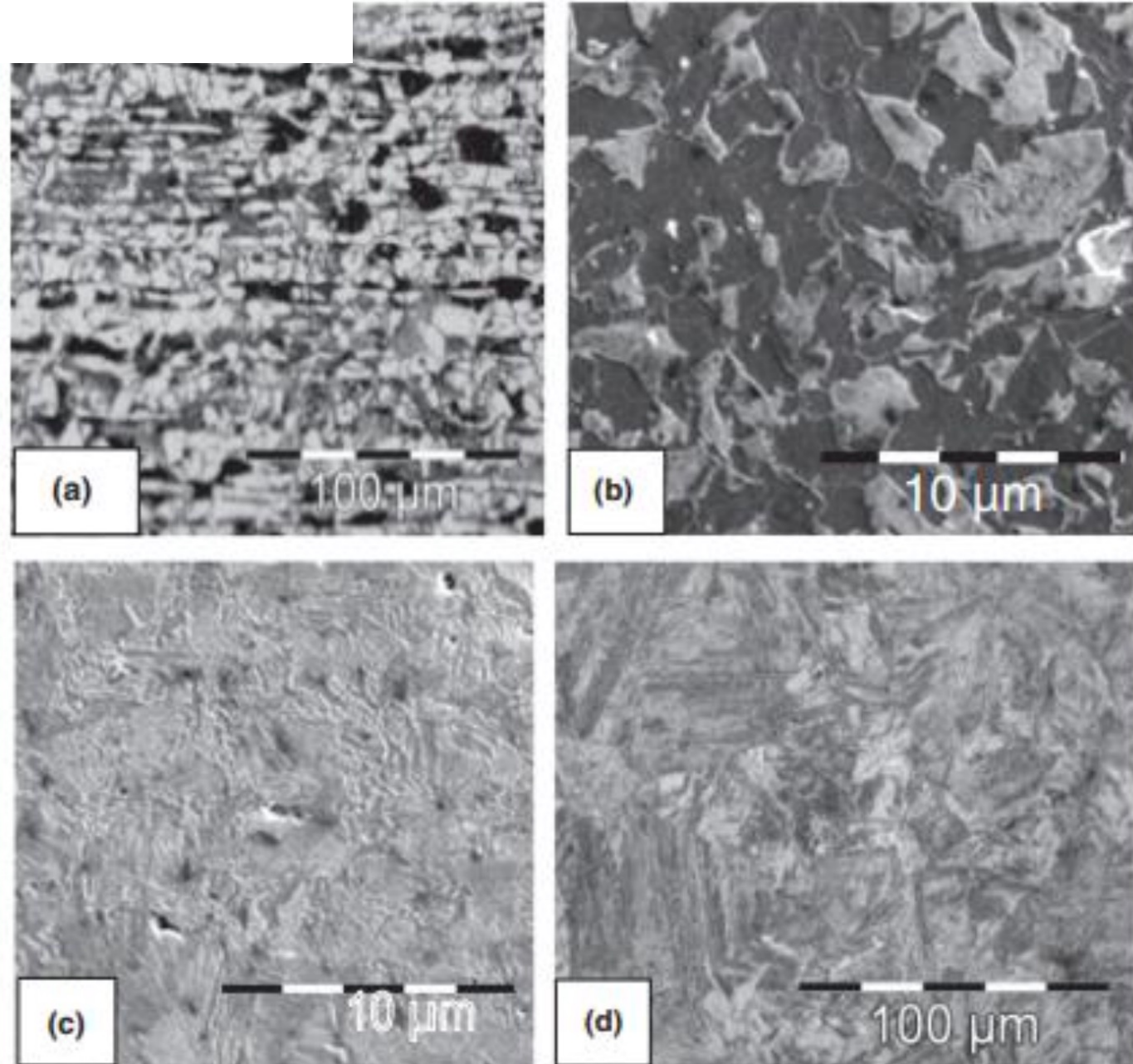
Electron micrograph of tempered martensite. Tempering was carried out at 594°C. The small particles are the cementite phase; the matrix phase is α -ferrite. 9300 \times . (Copyright 1971 by United States Steel Corporation.)



HEAT-TREATING

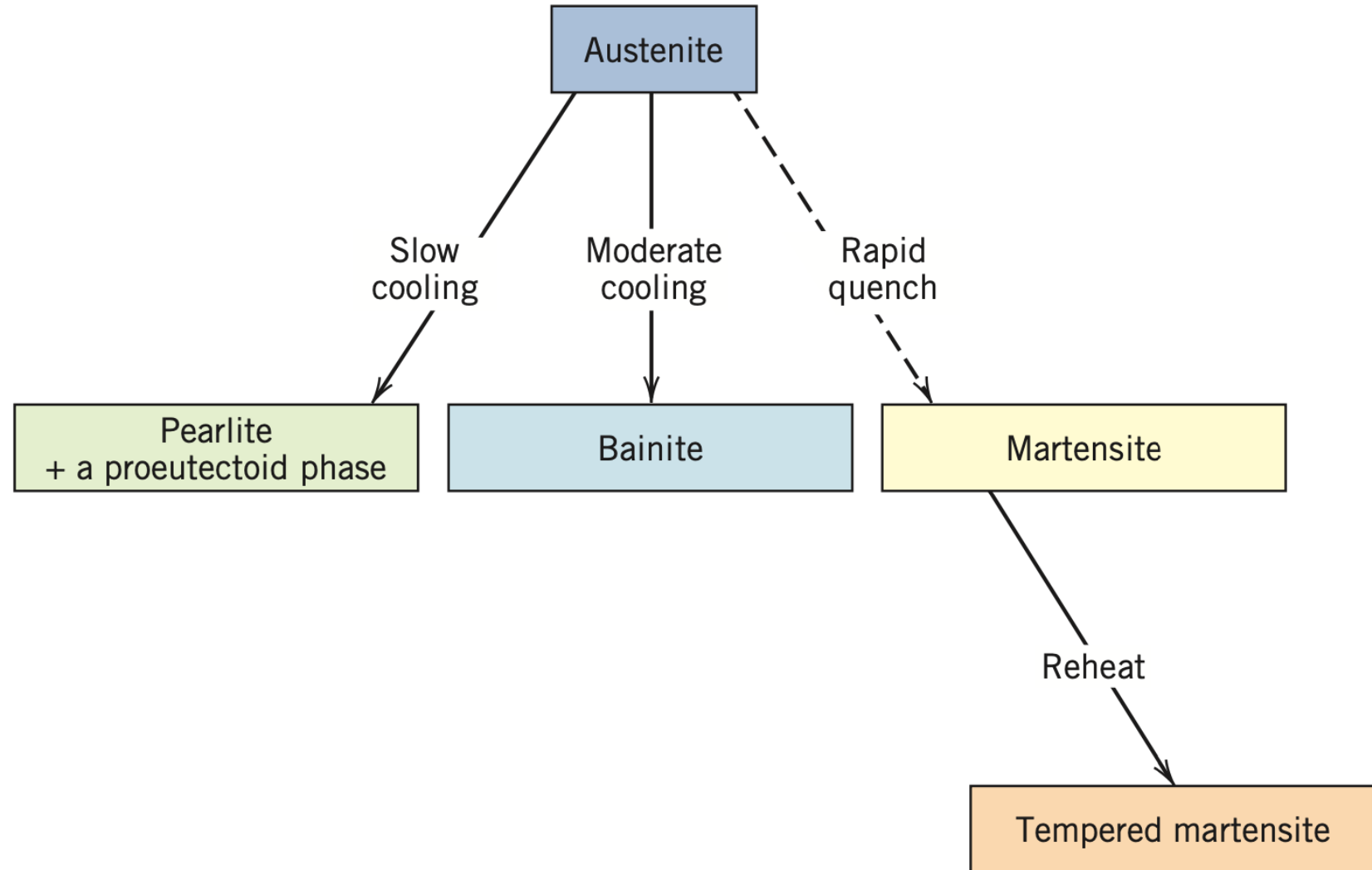
Figure: Optical micrographs of banded structure of C-Mn-Cr-B steel sample:

- a) As-received C-Mn-Cr-B steel sample,
- b) Ferrite-pearlite aggregate of the sample cooled at 1°C/s - Annealing
- c) Bainitic structure of the steel subjected to cooling rate of 10°C/s ,
- d) Martensitic structure at cooling



SUMMARY

Possible transformations involving the decomposition of austenite. Solid arrows, transformations involving diffusion; dashed arrow, diffusionless transformation.

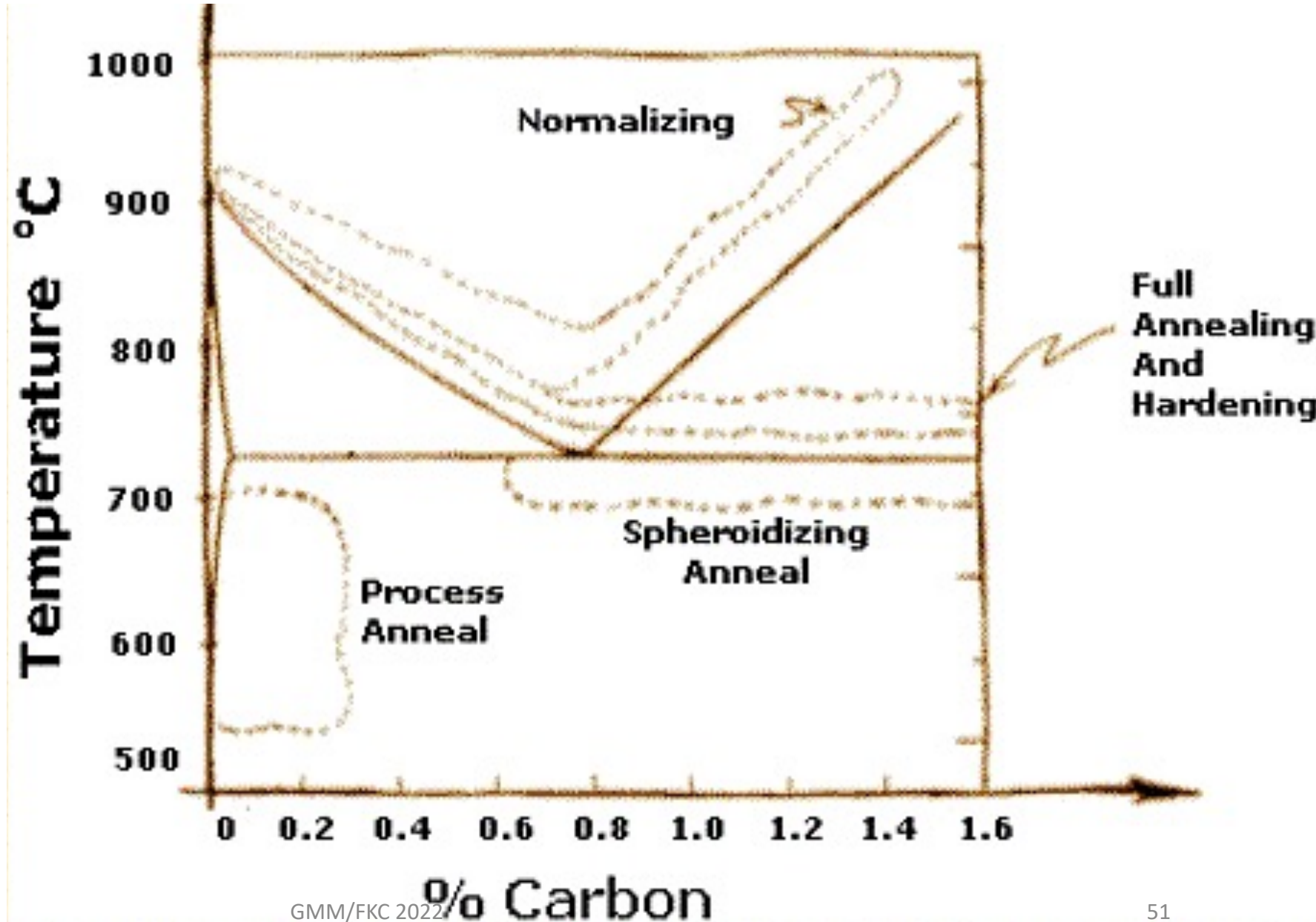


SUMMARY OF MICROSTRUCTURE AND MECHANICAL PROPERTIES OF IRON-CARBON ALLOYS

<i>Microconstituent</i>	<i>Phases Present</i>	<i>Arrangement of Phases</i>	<i>Mechanical Properties (Relative)</i>
Spheroidite	α -Ferrite + Fe ₃ C	Relatively small Fe ₃ C spherelike particles in an α -ferrite matrix	Soft and ductile
Coarse pearlite	α -Ferrite + Fe ₃ C	Alternating layers of α -ferrite and Fe ₃ C that are relatively thick	Harder and stronger than spheroidite, but not as ductile as spheroidite
Fine pearlite	α -Ferrite + Fe ₃ C	Alternating layers of α -ferrite and Fe ₃ C that are relatively thin	Harder and stronger than coarse pearlite, but not as ductile as coarse pearlite
Bainite	α -Ferrite + Fe ₃ C	Very fine and elongated particles of Fe ₃ C in an α -ferrite matrix	Hardness and strength greater than fine pearlite; hardness less than martensite; ductility greater than martensite
Tempered martensite	α -Ferrite + Fe ₃ C	Very small Fe ₃ C spherelike particles in an α -ferrite matrix	Strong; not as hard as martensite, but much more ductile than martensite
Martensite	Body-centered, tetragonal, single phase	Needle-shaped grains	Very hard and very brittle

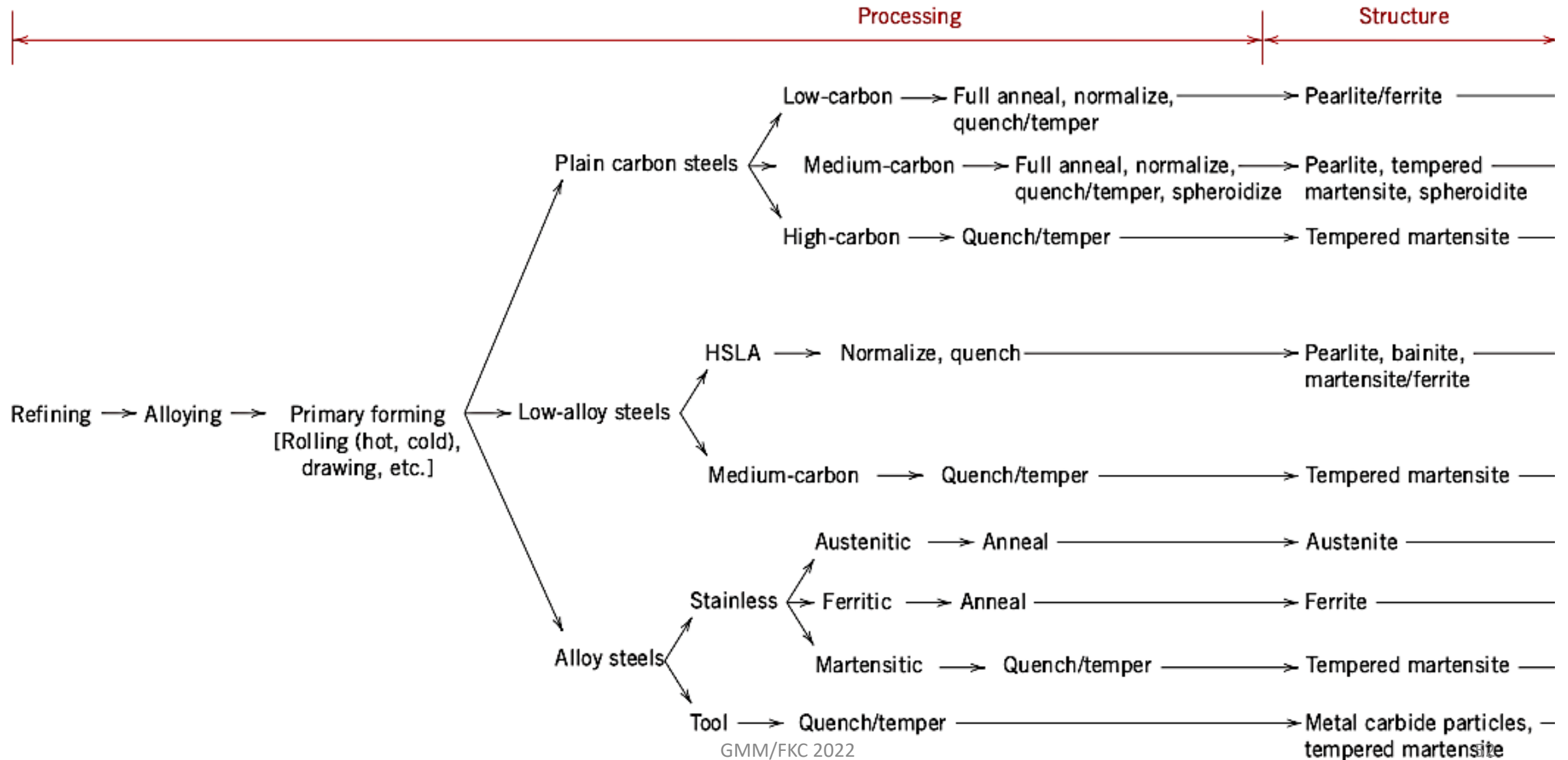
SUMMARY

Heat treatment methods and the temperature they are done on the Fe-C phase diagram.



SUMMARY

Schematic diagram that summarizes the elements of processing, structure, properties, and performance for steel alloys—from a materials engineering perspective.





END OF LECTURE 10