Mat E 272

Lecture 20: Thermal treatments (Chapter 11)

November 13, 2001

Introduction:

We know that the properties of materials can be affected by thermal history; steels offer an excellent example of this. For a given composition, different microstructures can be produced simply by varying the thermal processing parameters (for example, faster cooling rates, longer soak times, etc.) and these have a significant bearing on the mechanical properties. Consider a eutectoid steel (meaning a Fe-0.76 wt. % C alloy). If cooled at a fast rate, fine pearlite or even bainite is produced, which makes the material hard and strong. On the other hand, if the same material is slowly cooled, coarse pearlite is formed, which gives rise to more ductility but lower strength and hardness. The steel industry utilizes a number of standard heat treatments in order to produce specific microstructures for various applications. These will be discussed in today's lecture. In addition, a fourth type of strengthening mechanism, precipitation hardening, will also be discussed. (Do you recall what the other three hardening mechanisms are?) Precipitation hardening does not apply to all metal systems, only those described by a specific type of phase diagram. We will describe how precipitation hardening works and how to determine its applicability for a given alloy system.

Types of thermal treatments for steel

Purpose:

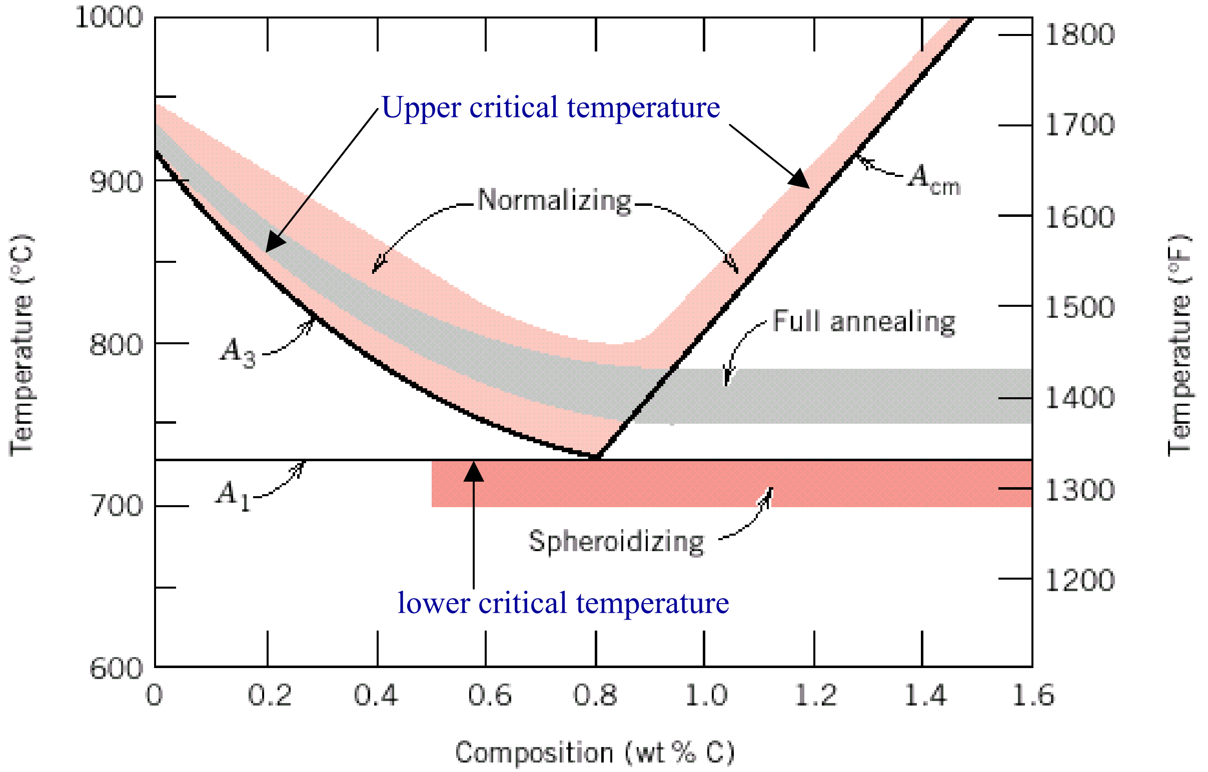
Thermal treatment (also called heat treatment or annealing) is performed in order to produce a specific, desired microstructure in a material.

Compositions:

Most of the steel alloys of industrial interest have a composition near the eutectoid (0.76 wt. % C). Consequently, we will focus our attention in this portion of the phase diagram.

Definitions:

The α - (α + γ) phase boundary is called the **A3**; the γ - (γ + Fe_3C) phase boundary is called the **Acm**; and the eutectoid isotherm is called **A1**.



This is a portion of the $Fe\text{-}Fe_3C$ phase diagram in the vicinity of the eutectoid (at 0.76 wt. % C)

Types of thermal treatments in steels

Normalizing:

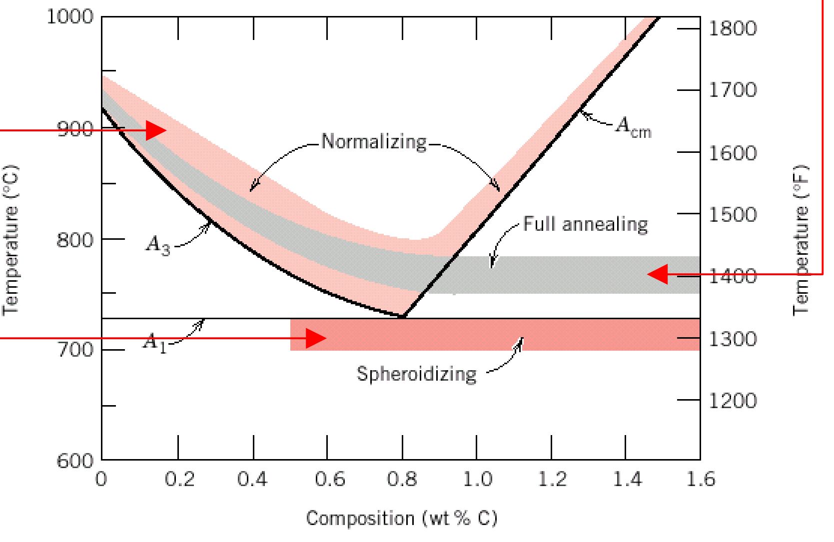
Applied in order to promote nucleation of new, stress-free grains following plastic deformation (rolling). New grains are smaller than the existing deformed grains. This is performed at a temperature of 55 to 85 deg. C above the upper critical temperature (A3 or Acm).

Spheroidizing:

The purpose of a spheroidizing heat treatment is to produce the *lowest hardness* possible for a given composition. This places the steel in its most workable condition for machining or other operations. (Recall the spheroidized microstructure shown in the previous lecture.) The steel is heated to just below the A1 where the Fe_3C coalesces to form spherical inclusions. Usually held at temperature for a few hours.

Full Anneal:

Performed in order to obtain a relatively soft and ductile material with a uniform microstructure. The steel is austenitized by heating to 15 to 40 deg. C above the A3 or A1 and then slowly cooled. This results in coarse pearlite + proeutectoid phase (either ferrite or cementite, depending on composition). The steel is therefore amenable to shaping, forming.



Hardenability

Note:
heat treatments designed to produce martensite always involve quenching the steel to as low a temperature as possible in the least amount of time. This becomes a problem for "large" parts that have different cooling rates from the surface to the center. How do we address the issue of *non-uniform cooling* in terms of martensite production?

The ability of a particular steel to transform to martensite is referred to as its **hardenability**

"*Hardness*" and "*Hardenability*" ARE NOT SYNONOMOUS!!!

Hardness refers to the local resistance of a material to an imposed plastic deformation
Hardenability is a measure of an alloy's ability to be hardened by formation of martensite throughout.

Alloys that have a high hardenability will exhibit a high volume fraction of martensite from surface to center.

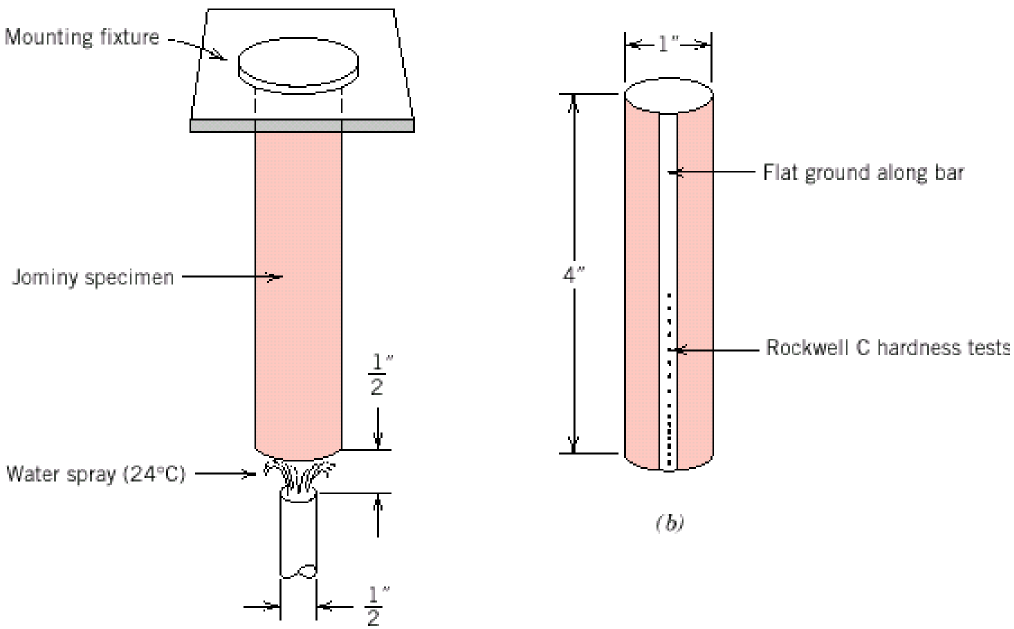
Hardenability - Jominy end-quench test

Problem:

How do we determine hardenability of a particular steel? This is equivalent to asking what effect different quench rates have on the microstructure throughout the alloy.

Solution:

If we take a standard cylindrical bar that has been uniformly heated to a given temperature, and then quench one end with a jet of water, the cooling rate within the bar will vary with distance from the quenched end. Since the hardness is a function of the volume fraction of martensite, by measuring hardness as a function of distance from the quenched end, we can construct a profile of martensite formation versus quench rate (or distance from the quenched end). This is called a Jominy end-quench test.



Standard Jominy end-quench test specimen

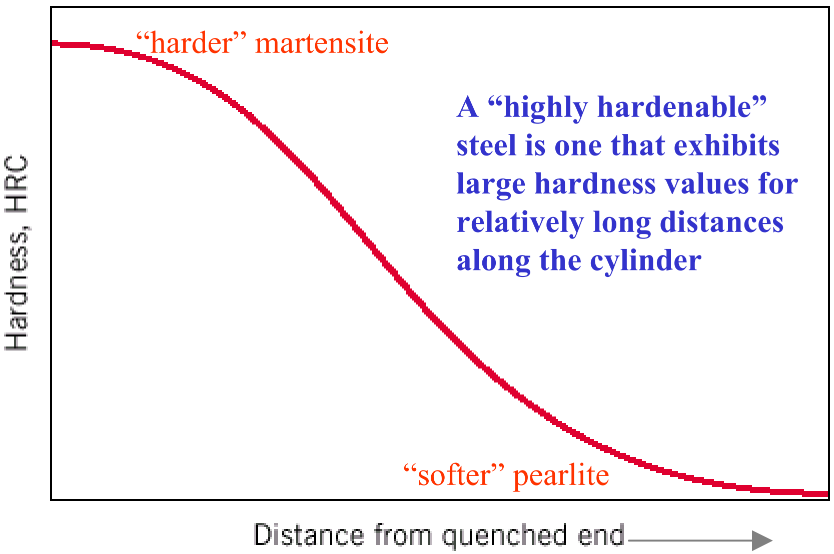
Sample geometry: 4” x 1” cylinder

after quenching, flats (0.015” deep) are ground into the cylinder from which hardness measurements are made.

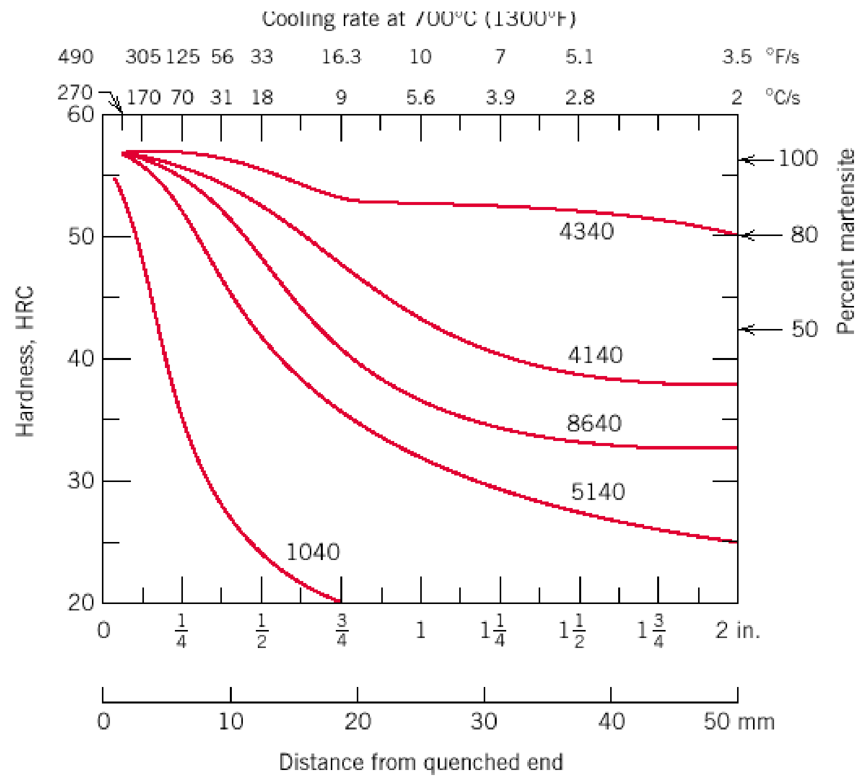
Hardenability - Jominy end-quench test

Test results:

The Jominy end-quench test allows determination of hardness vs. position along the axis of the cylinder. When this data is plotted out, a **hardenability curve** is generated:



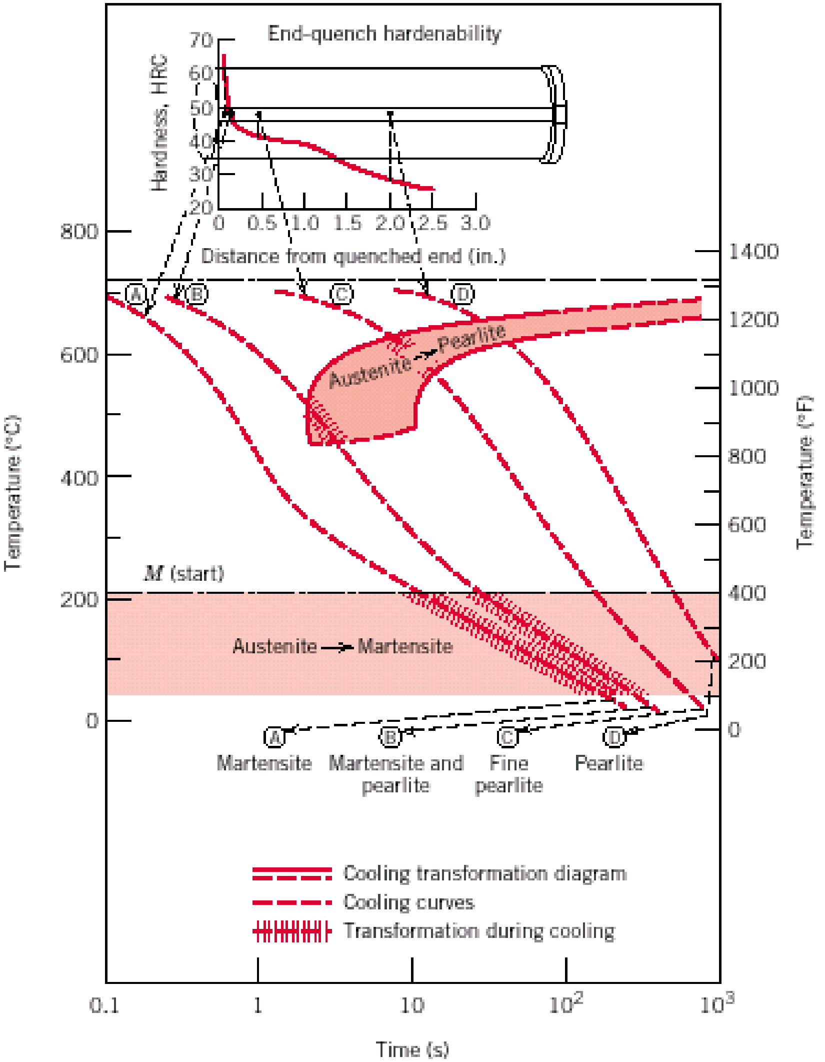
This is a series of hardenability curves obtained on various types of steels. Note that the "4340" curve reflects a higher "hardenability" than the "1040." Do you understand why this is so?



Hardenability

Interpretation:

One can correlate the results of a Jominy end-quench test (meaning hardness as a function of length along the cylinder axis) with microstructure by plotting cooling rate at each position on a continuous cooling curve for this composition:

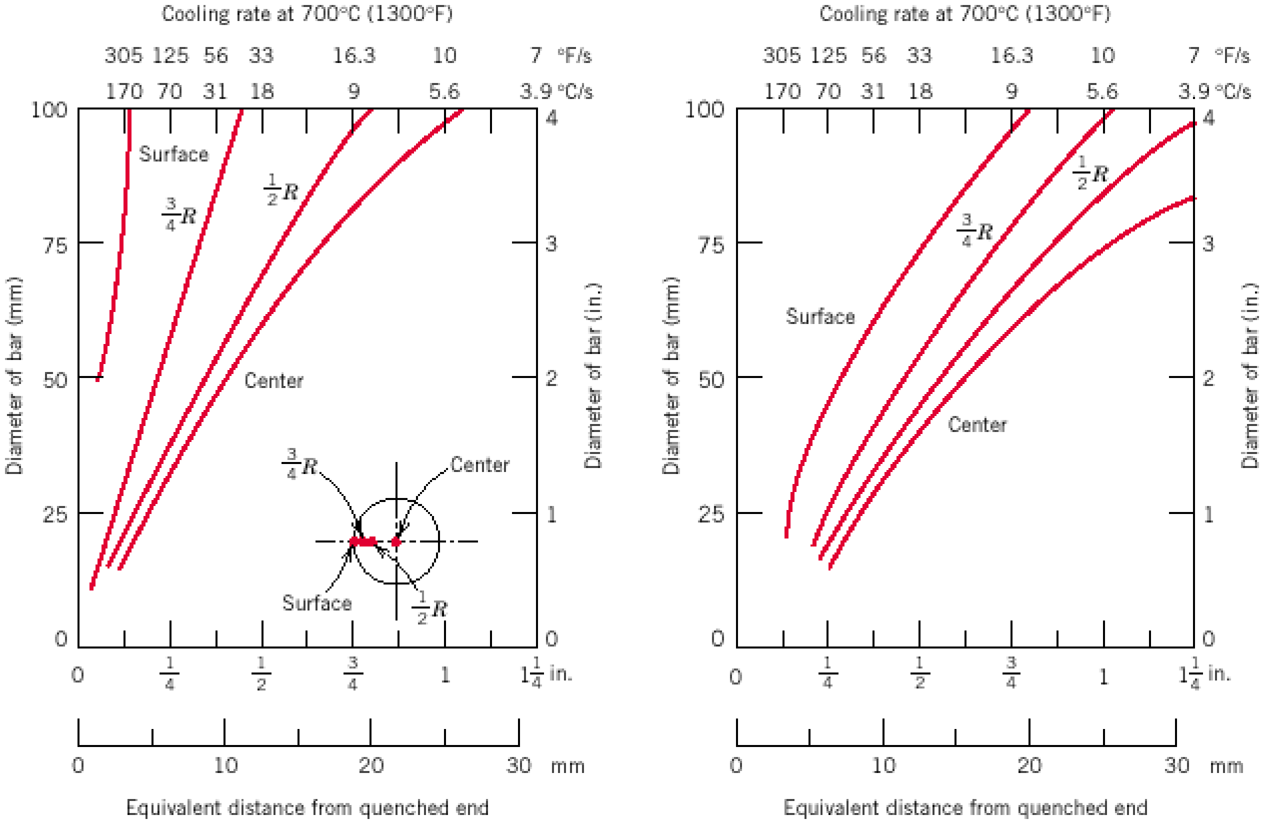


In the figure to the right, the quenched end cools at the fastest rate, corresponding to curve "A" which results in transformation of austenite to martensite.

Points "B," "C," and "D" along the cylinder experienced progressively slower cooling rates and as such, translate into the corresponding cooling curves and an increasing fraction of (softer) pearlite.

Influence of Specimen Size & Geometry

Since heat must be transported to the surface before it can be dissipated, cooling rate depends on the *surface to volume ratio*; the higher this quantity, the more rapid the rate of heat extraction and consequently the hardness. We can plot cooling rate as a function of diameter at various radial positions from the surface to the center: (this example shows cooling rates from 700^{o}C in mildly agitated water (left) and oil (right)).



Radial hardness profiles

To illustrate the difference in hardenability between two steels (plain carbon “1040” and alloy “4140”), hardness as a function of radial distance is plotted for each composition for a 50 mm and a 100 mm diameter cylinder.

Note that the alloy steel (the 4140) exhibits a higher hardenability than the plain carbon steel.

The center always cools at a slower rate than the surface; consequently, the center is of a lower hardness.

These curves are obtained from the hardenability curves, shown on the previous slide.