

Heat Treatment

Heat treating is a process utilized to change certain characteristics of metals and alloys in order to make them more suitable for a particular kind of application. In general, heat treatment is the term for any process employed which changes the physical properties of a metal by either heating or cooling.

When properly performed, heat treating can greatly influence mechanical properties such as strength, hardness, ductility, toughness, and wear resistance. The large number of service requirements and amount of alloys available make for a considerable variety of heat treating operations.

Heat Treatment of Carbon Steels and Carbon Alloy Steels

Most carbon steels and carbon alloy steels can be heat treated for the purpose of improving mechanical properties such as tensile and yield strength. This is accomplished due to the heat treatment fundamentally altering the microstructure of the steel.

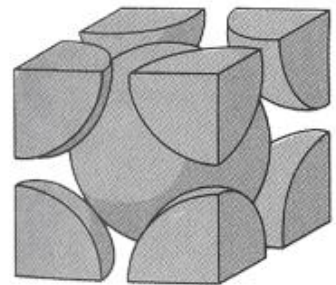
To discuss heat treating, one must begin with an understanding of the structure and phases of metals.

The structure of steel is composed of two variables:

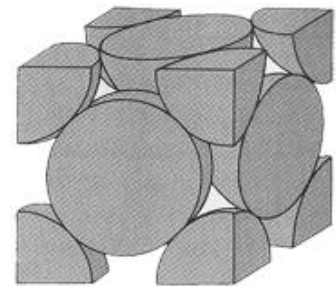
1. Grain Structure - The arrangement of atoms in a metal.
2. Grain Size - The size of the individual crystals of metal. Large grain size is generally associated with low strength, hardness, and ductility.

The crystals in steel have a defined structure that is determined by the arrangement of the atoms. There are two common crystal structures in iron: **body-centered-cubic (BCC)** and **face-centered-cubic (FCC)**. When the iron is arranged in the FCC structure it is able to absorb higher amounts of carbon than a BCC structure because of an increase in interstitial sites where carbon can sit between the iron atoms. During the alloying process elements such as carbon are introduced to the metal. These alloying elements interrupt the geometry of the individual crystal structures therefore increasing strength. Thus, using the change in crystal structure is critical to successful heat treating.

Steel can exist in various phases: ferrite, austenite, and cementite. To better understand these phases, look at the Iron-Carbon Phase Diagram. The Y-axis (vertical) is a measurement of temperature while the X-axis (horizontal) is a measurement of the carbon content of the steel. The far left hand side of the X-axis represents the **ferrite** phase of steel (low carbon content) while the far right hand side represents the **cementite** phase of steel (high carbon content), which is also known as iron carbide. The austenite phase is located between the dashed phase lines and occurs only above 1333 °F.



Body-Centered Cubic (BCC)

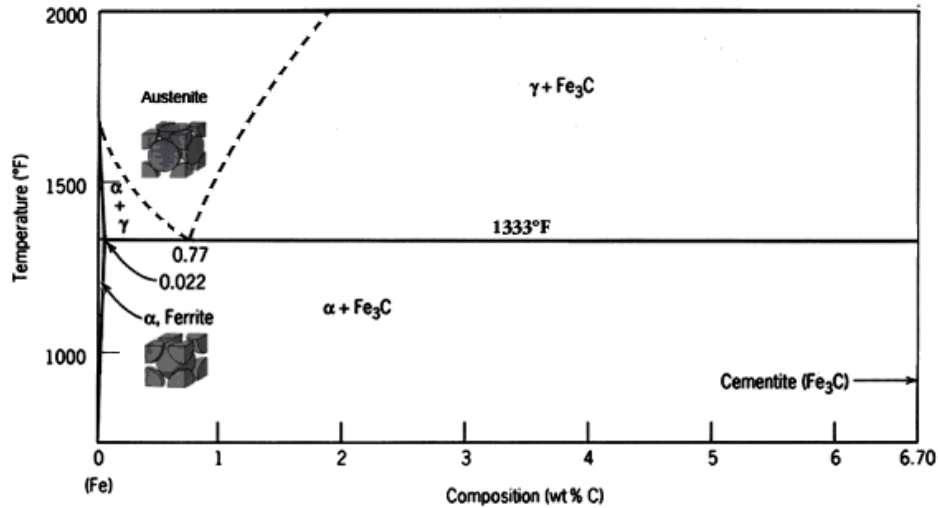


Face-Centered Cubic (FCC)

The transformation from BCC to FCC provides more points (spaces between spheres) for carbon to interact with the iron.

Source: *Materials Science and Engineering 3rd Ed.* William D. Callister Jr., 1994

Iron-Carbon Phase Diagram



Adapted from *Materials Science and Engineering 3rd Ed.* William D. Callister., 1994

When ferrite (low carbon steel) is at room temperature, it has a body-centered-cubic structure, which can only absorb a low amount of carbon. Because ferrite can only absorb a very low amount of carbon at room temperature, the un-absorbed carbon separates out of the body-centered-cubic structure to form carbides which join

together to create small pockets of an extremely hard crystal structure within the ferrite called cementite. However, when ferrite is heated to a temperature above the transformation line (horizontal line at 1333 °F) the body-centered-cubic structure changes to a face-centered-cubic structure known as austenite, thus allowing for absorption of the carbon into the crystal structure.

Once the steel enters the austenitic phase, all of the cementite dissolves into austenite. If the steel is allowed to cool slowly, the carbon will separate out of the ferrite as the cubic-structure reverts from face-centered back to body-centered. The islands of cementite will reform within the ferrite, and the steel will have the same properties that it did before it was heated. However, when the steel is rapidly cooled, or



A large specimen will cool more slowly at its core, causing a decrease in strength at the center of the piece.

quenched, in a quenching medium (such as oil, water, or cold air) the carbon does not have time to exit the cubic structure of the ferrite and it becomes trapped within it. This leads to the formation of **martensite**; the microstructure that produces the most sought after mechanical properties in steel fasteners.

During quenching it is impossible to cool the specimen at a uniform rate throughout. The surface will always cool more rapidly than the interior of the specimen. Therefore, the austenite will transform over a range of temperatures, yielding a possible variation of microstructure and properties depending on the position within the material.

The successful heat treatment of steels to produce a predominantly martensitic microstructure throughout the cross section depends mainly on three factors:

1. The composition of the alloy
2. The type and character of the quenching medium
3. The size and shape of the specimen

Hardenability is the ability of a steel to transform into martensite with a particular quenching treatment. This is directly affected by the alloy composition of the steel. For every different steel alloy there is a

specific relationship between its mechanical properties and its cooling rate. Hardenability is not “hardness” which is a resistance to indentation; rather, hardness measurements are utilized to determine the extent of a martensitic transformation in the interior of the material. A steel alloy that has a high hardenability is one that hardens, or forms martensite, not only at the surface but also to a large degree throughout the entire interior. In other words, hardenability is a measure of the degree to which a specific alloy may be hardened.

The newly formed martensite is considered a grain structure (or microstructure), not a phase and is very hard and brittle. Due to the brittleness inherent in martensite, steel that has been quenched from austenitizing temperatures will require tempering before it can be placed into service. **Tempering** involves heating the steel to a specific temperature below that of the transformation line and allowing it to cool slowly. This causes the crystal structure to relax, thereby increasing the ductility and decreasing the hardness to specified levels. The specific tempering temperature will vary based on the desired results for the steel.

The following example will demonstrate the effectiveness of tempering:

ASTM A193 Grade B7, SAE J429 Grade 8 and ASTM A574 Socket Head Cap Screws are all made from alloy steels. In fact some alloy steel grades can be used to manufacture any of the three final products: such as 4140 and 4142 alloy steel. The final mechanical properties appear in the table.

The initial heat treating process is relatively the same for all three products. The parts are heated until fully austenitized and then are quenched in oil and tempered.

Fasteners Produced From AISI 4140 & 4142 Steel			
Fastener	ASTM A193 B7	SAE J429 Gr. 8	ASTM A574 SHCS
Tempering Temp.	1150° F	800° F	650° F
Tensile Strength	125,000 PSI min. (2 ½in. and under)	150,000 PSI min.	180,000 PSI min. (through ½in.) 170,000 PSI min. (above ½in.)
Yield Strength	105,000 PSI min. (2 ½in. and under)	130,000 PSI min	153,000 PSI min.
Proof Strength	N/A	120,000 PSI	140,000 PSI (through ½in.) 135,000 PSI (above ½in.)
Hardness	HRC 35 max.	HRC 33-39	HRC 39-45 (through ½in.) HRC 37-45 (above ½in.)

This tempering temperature dictates the final mechanical properties. The following are the minimum tempering temperatures per each specification:

- B7: 1150 °F
- Grade 8: 800 °F
- SHCS: 650 °F

A lower tempering temperature will produce a harder and higher tensile strength part for these alloy steels. However, the lower tempering temperatures will also mean lower ductility, impact strength, operating temperature, and possibly lower fatigue life. For example, socket head cap screws and Grade 8's have an operating temperature limitation of approximately 450 °F, whereas B7 is able to function properly up to approximately 800 °F.

Annealing is a heat treating process used to soften previously cold-worked metal by allowing it to recrystallize. 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. Ordinarily, annealing is carried out to (1) relieve stresses (often introduced when cold-working the part); (2) increase softness, ductility and toughness; and/or (3) produce a desired microstructure. A variety of annealing heat treatments are possible.

Any annealing process consists of three stages:

1. heating to the desired temperature
2. holding or “soaking” at that temperature
3. slowly cooling, usually to room temperature

Time is the important parameter in these procedures

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.

Stress relieving is an annealing process that is utilized when internal residual stresses develop in metal pieces in response to such things as cold working. Failure to remove these internal stresses may result in distortion and warping. The internal stresses are relieved by bond relaxation as a result of heating. A stress relief is carried out by heating the piece to a recommended temperature (approximately 165 °F below the transformation temperature for carbon steels), holding the work piece at temperature long enough to attain a uniform temperature throughout the part, and finally cooling to room temperature in air. Stress relieving can eliminate some internal stresses without significantly altering the structure of the material.

Steels that have been plastically deformed (e.g.: by a rolling operation) consist of grains of pearlite, which are irregularly shaped and relatively large, but vary substantially in size. **Normalizing** is an annealing heat treatment used to refine the grains and produce a more uniform and desirable size distribution.

Normalizing is accomplished by heating the material to a temperature above its upper critical temperature (e.g.: just above 1333°F for most fastener-related steels). After sufficient time has been allowed for the alloy to completely transform to austenite, the metal is allowed to cool in the air.

Medium and high carbon steels having a microstructure containing coarse **pearlite** may still be too hard to conveniently machine or plastically deform. These steels (and in fact, any steel) may be annealed to develop the spheroidite structure. **Spheroidized** steels have a maximum softness and ductility and are easily machined or deformed.