

**Metallurgy of Steel for Bladesmiths & Others
who Heat Treat and Forge Steel**

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Preface

For the past 15 years or so I have been working with practicing bladesmiths on problems related to forging and heat treating steel blades. It has become apparent to me in that time that there is a need for a book that explains the metallurgy of steel for people who heat treat and forge steels and have had no formal metallurgical education. This book is an effort to provide such a treatment. I have discovered that bladesmiths are generally very quick to catch on to the ideas of metallurgy and consequently an attempt was made to set the level of detail presented here for the needs of those wanting a fairly complete understanding of the subject.

Most chapters in the book contain a summary at the end. These summaries provide a short review of the contents of each chapter. It may be useful to read these summaries before and perhaps after reading the chapter contents.

The Materials Information Society, ASM International, has published a book that contains a wealth of information on available steels and is extremely useful to those who work and heat treat steel: Heat Treater's Guide, Practices and Procedures for Irons and Steels, 2nd Edition, (1995), Materials Park, OH 44073. A major goal of this book is to provide the necessary background which will permit a practicing metal worker to understand how to use the information in the ASM book, as well as other handbooks published by ASM International.

I would like to acknowledge the help of two bladesmiths who have contributed to this book in several ways, Alfred Pendray and Howard Clark. Both men have helped me understand the level of work being done by U.S. bladesmiths and they have also contributed to some of the experiments utilized in this book. They are also responsible for the production of this book because of their encouragement to write it. In addition I would like to acknowledge many useful discussions with William Dauksch and my colleague, Prof. Brian Gleeson, who made many useful suggestions on the stainless steel chapter.

I am particularly indebted to Iowa State University and their Materials Science and Engineering Department for providing me with the opportunity to teach metallurgical engineering students about steel for over two decades, as well as to the Ames Laboratory, DOE, that supported most of my research activity. Many of the pictures and methods of presentation in this book result from my experience teaching students and doing research at Iowa State University.

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Index Index

Chapter	Title of chapter or subtopic	Page
1	Pure Iron	1
	Summary	4
2	Solutions and Phase Diagrams	5
	Solutions	5
	Phase Diagrams	6
	Summary	7
3	Steel and the Fe-C Phase Diagram	8
	Low Carbon Steels (Hyoeutectoid Steels)	10
	High Carbon Steels (Hypereutectoid Steels)	11
	Eutectoid Steels	13
	The A_1 , A_{e1} , A_{c1} , A_{r1} Nomenclature	15
	References	16
	Summary	17
4	The Various Microstructures of Room Temperature Steel	19
	Optical Microscope Images of Steel Grains	19
	Room Temperature Microstructures of Hypo- and Hypereutectoid Steels	20
	Microstructure of Quenched Steel	23
	Martensite	24
	Two Types of Martensite	25
	The M_s and M_f Temperatures	26
	Martensite and Retained Austenite	27
	Bainite	29
	Spheroidized Microstructures	32
	Summary	34
5	Mechanical Properties	36
	The Tensile Test	36
	The Hardness Test	38
	The Notched Impact Test	42
	Fatigue Failure and Residual Stresses	45
	References	47
	Summary	48
6	The Low Alloy AISI Steels	50
	Manganese in Steel	52
	Effect of Alloying Elements on Fe-C Phase Diagram	54
	References	56
	Summary	56
7	Diffusion	58
	Carburizing and Decarburizing	61
	References	63
	Summary	64
8	Control of Grain Size by Heat Treatment and Forging	66
	Grain Size	66
	Grain Growth	67
	New Grains formed by Phase Transformation	69
	New Grains formed by Recrystallization	70
	Effects of Alloying Elements	72
	Particle Drag	73
	Solute Drag	74
	References	76
	Summary	76
8	Hardenability of Steel	78
	IT Diagrams	79
	Hardenability Demonstration Experiment	83
	CT Diagrams	85
	The Jominy End Quench	88
	Hardenability Bands	91
	References	91
	Summary	92

10	Tempering	95
	Tempered Martensite Embrittlement (TME)	96
	Effect of %C on toughness	97
	Effect of Alloying Elements	98
	References	101
	Summary	101
11	Austenitization	103
	Single Phase Austenitization	103
	Homogenization	106
	Austenite Grain Growth	106
	Two-Phase Austenitization	108
	References	110
	Summary	110
12	Quenching	113
	Special Quenching techniques	113
	Martempering	114
	Austempering	115
	Variation on Conventional Austempering	117
	Characterization of Quench Bath Cooling Performance	120
	Oil Quenchants	122
	Polymer Quenchants	124
	Salt Bath Quenchants	124
	References	125
	Summary	126
13	Stainless Steels	128
	Ferritic Stainless Steels	129
	Martensitic Stainless Steels	132
	Optimizing Martensitic Stainless Steels for Cutlery Applications	134
	Example Heat Treatment using AEB-L	139
	Austenitic Stainless Steels	141
	Precipitation Hardening Stainless Steels (PHSS)	145
	References	147
	Summary	147
14	Tool Steels	151
	Tool Steel Classification	151
	The Carbides in Tool Steels	153
	Special heat treatment effects with tool steels	155
	References	157
	Summary	158
15	Solidification	159
	Factor 1 - Microsegregation	160
	Factor 2 - Grain Size and Shape	165
	Factor 3 - Porosity	166
	References	168
	Summary	168
16	Cast Irons	170
	Gray and White Cast Irons	171
	Ductile and Malleable Cast Iron	179
	References	182
	Summary	183
	Index	184
Appendix	A - Temperature Measurement	A1
	Thermocouples	A1
	Radiation Pyrometers	A3
	References	A7
	B – Stainless Steels for Knife-makers	B8

1 - Pure Iron

Most steels are over 95% iron, so a good starting point to understanding steel is to study the nature of solid iron. Consider the following experiment. A 1 inch diameter bar of pure iron is sectioned to form a thin disk in the shape of a quarter. A face of the disk is now polished on polishing wheels starting first with a coarse grit polish and proceeding in steps with ever finer grits until one ends up with the face having the appearance of a shiny mirror. The shiny disk is now immersed for around 20-30 seconds in a mixture of 2 to 5 % nitric acid (HNO_3) in methyl alcohol (called nital, nit for the acid and al for the alcohol), a process known as etching. The etch causes the shiny surface to become a dull color. If the sample is now viewed in an optical microscope at a magnification of 100x, it is found to have the appearance shown on the right of Fig. 1. The individual regions such as those numbered 1 to 5 are called iron grains and the boundaries between them,

such as that between grains 4 and 5 highlighted with an arrow, are called grain boundaries. The average size of the grains is quite small. At the 100x magnification of this picture a length of 200 microns is shown by the arrow so labeled. The average grain diameter for this sample has been measured to be 125 microns, where 1 micron = 0.001 mm. Although a small number, this grain size is much larger than most commercial irons. (It is common to use the term μm for micron and $25 \mu\text{m} = 0.001 \text{ inches} = 1 \text{ mil}$. The thickness of aluminum foil and the diameter of a hair both run around $50 \mu\text{m}$.)

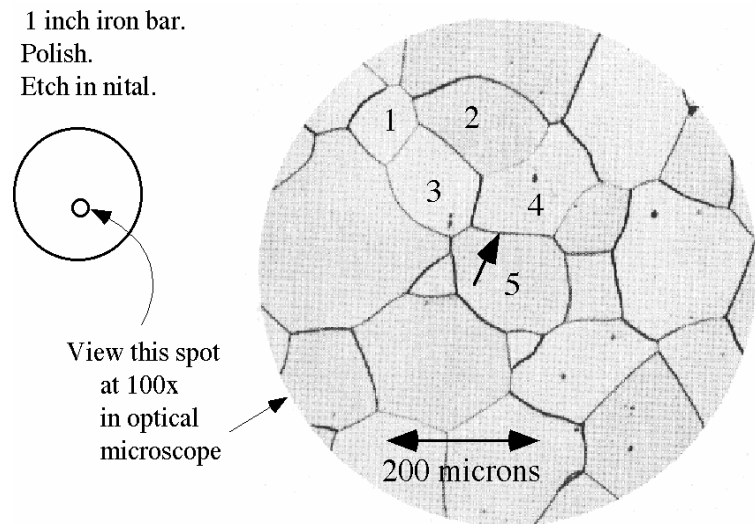


Figure 1.1 Optical microscope image of surface of a polished and etched iron bar viewed at a magnification of 100x. [1.1]

The basic building blocks of solids like salt and ice are molecules, which are units made up of two or more atoms. For example, sodium + chlorine in table salt (NaCl) and hydrogen + oxygen in ice (H_2O). In metals, however, the basic building blocks are the individual atoms of the metal, i.e., iron (Fe) atoms in a bar of iron, or copper (Cu) atoms in copper wire. Each one of the grains in Fig. 1.1 is what we call a crystal. In a crystal made up of atoms, all of the atoms are uniformly arranged on layers. As shown in Fig. 1.2, if you draw lines connecting the centers of the atoms you generate a 3-dimensional array of little cubes stacked together to fill space. In iron at room temperature the cubes have an atom at each of the 8 corners and one atom right in the middle of the cube. This crystal structure is called a BCC (body centered cubic) structure, and the geometric arrangement of atoms is often called a BCC *lattice*. Notice that the crystal lattice can be envisioned as 3 sets of intersecting planes of atoms with each plane set parallel to one face of the cube. Iron with a BCC structure is called *ferrite*. Another name for ferrite is alpha iron, or α -iron, where α is the symbol for the Greek letter a.

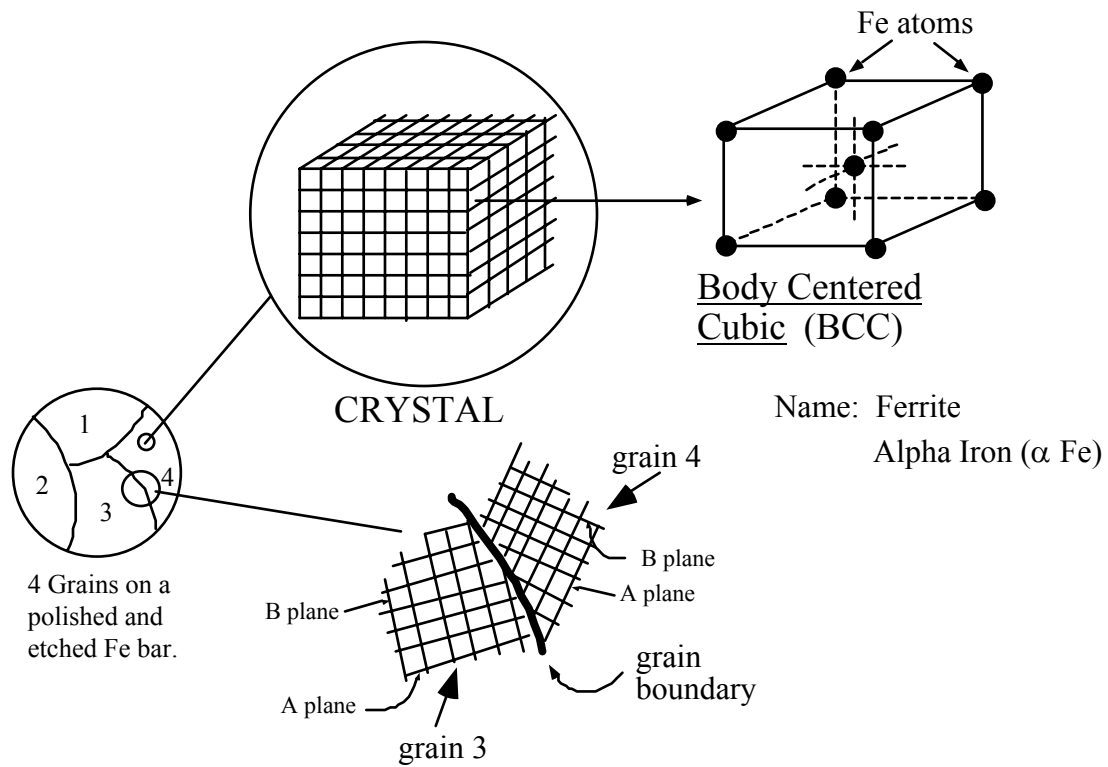
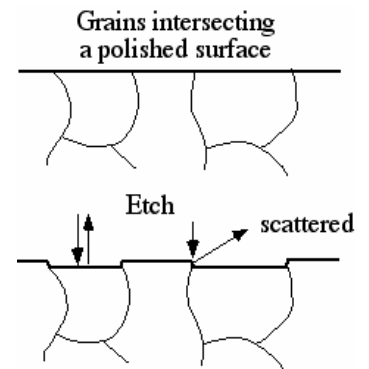


Figure 1.2 The crystal structure of the grains and the nature of the grain boundaries.

The nature of a grain boundary is illustrated at the bottom center of Fig. 1.2. The boundary is a planar interface, generally curved, along which two grains of different orientation intersect. The A planes in grain 4 make a much steeper angle with the horizontal than do the A planes of grain 3. If grain 4 were rotated clockwise to cause its A planes to line up with the A planes of grain 3, then the grain boundary would go away and the 2 grains would become one larger grain. An interesting question is why do these grain boundaries show up on the etched surface? When a metal is etched in an acid, atoms are chemically removed from the surface. It turns out that the rate of removal of iron atoms by nitral depends on the orientation of the crystal that is facing the acid. Because each grain presents a different orientation, each grain etches down at a different rate. For example, the planes that form the faces of the body centered cubes etch far slower than other crystal planes. Hence, after a period of etching small steps develop at the grain boundaries. For example, at the boundary of a fast etching grain, one would see a step -up to the surrounding grains. The step generally causes light to be scattered away from your eye and you see the boundaries as dark lines.



If iron is heated to 912 °C (1674 °F) a somewhat magical effect occurs, the crystal structure changes spontaneously from body centered cubic to a new structure called face centered cubic (FCC). This structure is shown in Fig. 1.3, where it is seen that, as the name suggests, the atoms lie on the corners of a cube as well as one atom at each of the 6 faces of the cube. Like

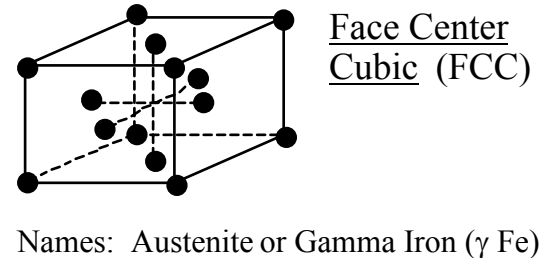


Figure 1.3 The crystal structure of iron that forms at high temperatures.

the low temperature BCC structure, this structure has two names, either *austenite* or gamma iron (γ iron), where γ is the symbol for the Greek form of the letter c.

Historical Note: The first 3 letters of the Greek alphabet are alpha, beta, gamma (α , β , γ) but there is no structure of iron called beta iron. When the structure of iron was being discovered in the late 19th century, the magnetic transition in iron which occurs at 770 °C (1418 °F), caused scientists to theorize a structure of iron they called beta iron, which was later shown not to exist.

When the ferritic iron is heated to 912 °C (1674 °F) the old set of ferrite grains changes (transforms) into a new set of austenite grains. Imagine that the ferrite grain structure shown in Fig. 1.2 has just reached the transformation temperature. What one would see is, first, the formation of a new set of very small austenite grains forming on the old ferrite grain boundaries, and second, the growth of these grains until all the old ferrite grains were gone. Two important effects occur when ferrite changes to austenite. (1) Just like it takes heat energy to transform ice to water, it takes heat energy to change the ferrite grains into austenite grains. Therefore, on heating, the iron temperature will remain close to 912 °C (1674 °F) until all the ferrite grains are transformed. (2) The ferrite to austenite (α to γ) transformation is accompanied by a volume change. The density of austenite is 2% higher than ferrite, which means that the volume per atom of iron is less in austenite.

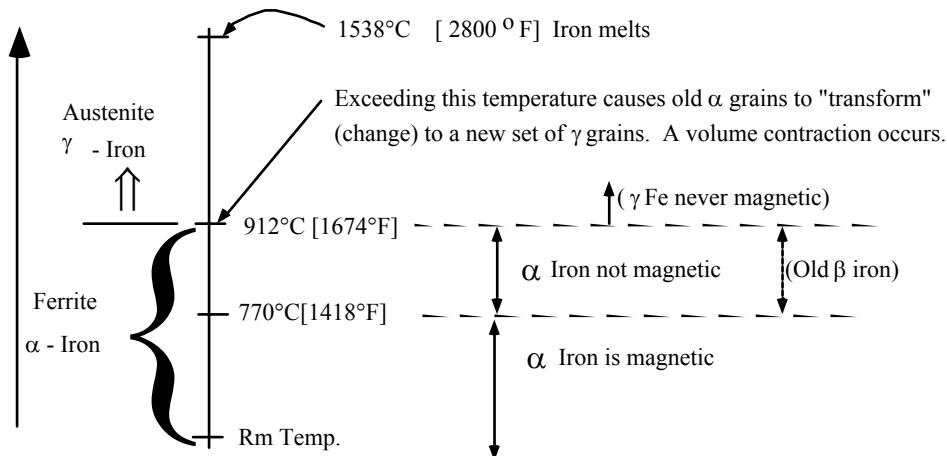


Figure 1.4 Changes occurring in iron shown on a plot of increasing temperature.

It is helpful to represent the ideas discussed above geometrically on a diagram where one plots temperature on a vertical scale and identifies the changes that occur at significant temperatures, as shown in Fig. 1.4. Following are two experiments one can do to illustrate these changes. Exp. 1: Heat a bar of iron up above 1418 °F (770 °C) and as it cools place a magnet near it. When the temperature reaches 1418 °F (770 °C) the hot sample will begin to become pulled toward the magnet. As the diagram of Fig. 1.4 shows, BCC iron (α iron) is only magnetic below 1418 °F (770 °C), and FCC iron (γ iron) is never magnetic. Exp. 2: Obtain a piece of black (non-galvanized) iron picture wire and string it horizontally between 2 electrical posts spaced 3 feet apart. Hang a weight from the center of the wire and pass an electrical current through the wire heating it above 1674 °F (912 °C), which will be past a red color to an orange-yellow color. (Note:

You will need to increase the voltage slowly using a high current capacity variable power source, such as a variac.) As you heat the wire it expands and the weight drops. Now turn off the power and watch the wire cool in a darkened room. You will see the above two effects that occur at the 1674 °F (912 °C) transformation temperature. 1) As the wire cools the accompanying volume contraction will raise the center weight, but this rising will be temporarily reversed when the wire expands as the less dense ferrite forms. 2) Heat liberated by the transformation will cause a visible pulse of color temperature increase to be seen in a darkened room. Both of these effect can be observed in reverse order on heating, but they are less dramatic due to the difficulty of heating rapidly. You can understand why heat is given off when austenite changes to ferrite on cooling by thinking about the water-ice transformation. It is clear that one needs to cool water to make it transform to ice (freeze). This means heat is removed from the liquid at the freezing temperature. The same effect occurs when metals freeze, heat is removed from the metal. So when a hot metal cools to its freezing point we find that heat is given off from the freezing liquid. The transformation from liquid to solid is a **phase transformation** between the liquid phase and the solid phase. Phase transformations that occur on cooling liberate heat. When austenite transforms to ferrite on cooling we have a solid-solid (rather than a solid-liquid) phase transformation and heat is liberated. On heating the reverse occurs, heat is absorbed when ferrite goes to austenite.

References

1.1 Metals Handbook, Volume 7, 8th Edition, ASM (1972).

Summary of the major ideas of this chapter.

- 1 A piece of iron consists of millions of small crystals all packed together.
- 2 Each crystal is called a **grain**. A typical grain diameter is 30 to 50 microns.
(25 micron = 25 μm = 0.001inch = 1 mil)
- 3 The boundaries between the crystals are called **grain boundaries**.
- 4 Below 1167 °F (912 °C) iron is called either **ferrite** or **alpha** (α) iron. The iron atoms in ferrite are arranged on a body center cubic (BCC) geometry. It is common to call the arrangement of atoms a body centered cubic (BCC) **lattice**.
- 5 Above 1167 °F (912 °C) iron is called either **austenite** or **gamma** (γ) iron. The iron atoms in austenite are arranged on a face center cubic (FCC) lattice.
- 6 Heating ferrite to 1167°F (912 °C) causes tiny grains of austenite to form on the ferrite grain boundaries. Continued heating causes these new γ grains to grow converting all the old α grains into a new set of smaller γ grains. On cooling below 1167 °F (912 °C) the same type of change occurs, but in reverse order, where α grains replace γ grains.

2 - Solutions and Phase Diagrams

In order to understand how the strength of steels is controlled it is extremely useful to have an elementary understanding of two topics: Solutions and Phase Diagrams.

Solutions

The idea of a solution can be explained by the following simple example. Take a glass of water and put a tea spoon full of either sugar or salt into it. Initially you will be able to see most of the solid white sugar or salt floating on the water or sinking to the bottom of the glass. However, after stirring with the spoon adequately you will see that all of the sugar or salt disappears and you only see the clear water that you started with. We say that the sugar or salt has *dissolved* into the water and the final liquid is said to be a *solution* of sugar or salt in water.

What has happened to the sugar or salt? Consider the salt because its molecule (sodium chloride [NaCl] for table salt or calcium chloride [CaCl₂] for the salt used on icy roads) is more simple than sugar. When the salt goes "into solution" the individual molecules break apart into their component atoms and these atoms in-turn are pulled into the liquid water and are trapped in the water as charged atoms (called ions) between the water molecules [H₂O] that make up the liquid we call water. For table salt the NaCl molecules decompose following the reaction: $\text{NaCl} \Rightarrow \text{Na}^+ + \text{Cl}^-$, where the symbol Na^+ refers to a positively charged sodium atom, called an ion, and the symbol Cl^- refers to a negatively charged chlorine atom. You no longer see the solid salt because the chemical bonds that held the atoms together in the solid have been relaxed causing the former solid structure to disappear as its component atoms became incorporated into the liquid water between the water molecules.

In general, when a solution is formed by dissolving something into a liquid the freezing temperature of the liquid will decrease. This, of course, is why we add calcium chloride (CaCl₂) salt to our streets and sidewalks during the winter months. The salt dissolves into the rain water and drops its freezing temperature so that ice will not form until the temperature has been lowered below the pure water freezing temperature of 32 °F (0 °C). This effect can be represented graphically as shown in Fig. 2.1. Here, temperature is plotted on the vertical axis and the amount of salt dissolved into the water on the horizontal axis. The amount of salt dissolved in the water is given here as a weight percent of the total liquid solution. Two terms are often used to

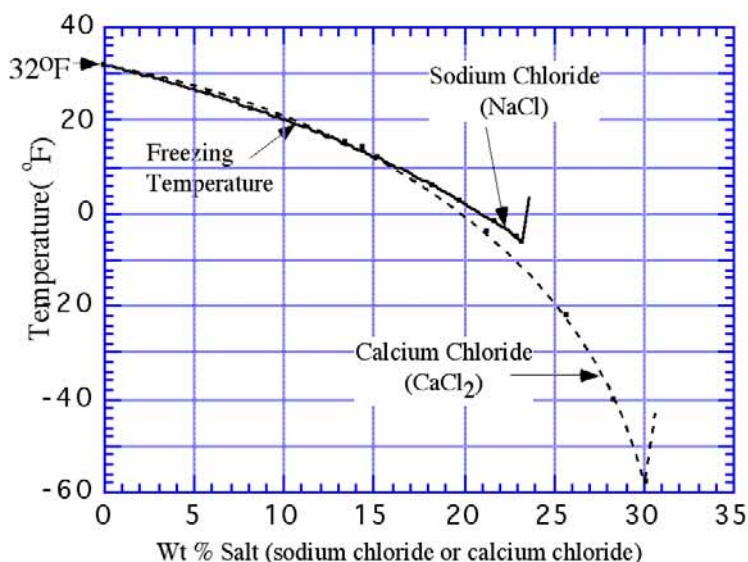


Figure 2.1 The lowering of the freezing temperature of water versus the weight % of two different salts dissolved in the water.

describe the amount of stuff that has been dissolved, A 10 wt. % sodium chloride value can be called the **concentration** of salt in the solution, or the **composition** of the solution. Notice on Fig. 2.1 that after a certain maximum amount of the salt has dissolved in the solution the freezing temperature suddenly begins to rise quite rapidly. This maximum composition is called the **eutectic** composition and it will be discussed more later. The curves show why it is preferable to use calcium chloride over sodium chloride to prevent ice formation on your sidewalks.

Phase Diagrams The geometric arrangement of the molecules in water (called the molecular structure) is the same, on average, from point to point in the water. The water is called a liquid **phase**. Similarly, the molecular structure in ice is the same from point to point in the ice, and the ice is called a solid phase. However, the molecular structures of ice and water are very different from each other, one being a liquid and the other a solid. Therefore, liquid water and ice are 2 different phases.

As shown in Fig. 2.1, the freezing point of water is suppressed as salt is dissolved into the water forming a solution. The molecular structure of the salt solution is essentially the same as that of pure water since the salt ions fit in-between the H₂O molecules without disturbing their geometric arrangement relative to each other. So pure water and the salt solution generated by dissolving salt in the water are the same phase.

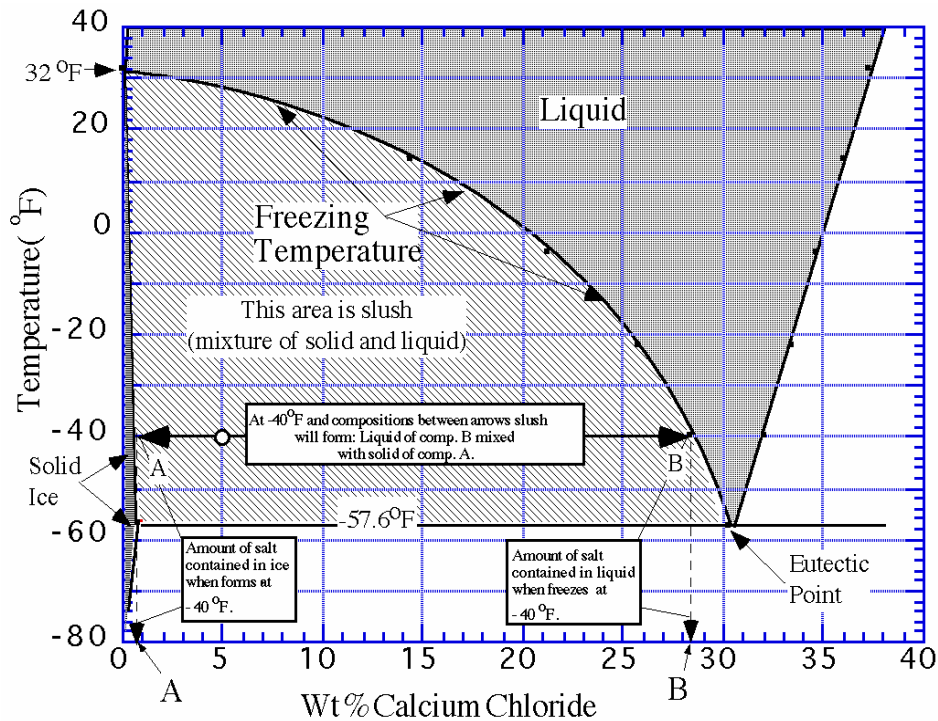


Figure 2.2 A portion of the water-calcium chloride phase diagram.

A phase diagram is a temperature versus composition map that locates on the map the temperature-composition coordinates where the various phases can exist. Fig. 2.2 presents part of the water-calcium chloride phase diagram. Just as in Fig. 2.1 the diagram has temperature plotted vertically and composition (in wt. % salt) plotted horizontally. The

freezing temperature line for the liquid salt solution is the same as on Fig. 2.1, only now the sharp rise in freezing temperature beyond the eutectic point is extended to the maximum temperature of the diagram. The shaded region labeled "Liquid" above the freezing temperature line maps out all possible temperature-compositions that are found to be liquid. Notice that at the extreme left of the diagram there is a thin shaded region labeled "Solid Ice". This solid ice has the same molecular structure as pure water ice, but now it contains a very small amount of salt dissolved in it. It is the same phase as the pure water ice. Hence this thin region is a map of where solid ice occurs on the diagram.

Now consider a salt solution containing 5 wt. % calcium chloride that is cooled to -40°F (small circle on Fig. 2.2). This point on the phase diagram map does not lie in either the liquid or the solid (ice) regions. Hence, this solution at -40°F cannot be all solid or all liquid. Figure 2.2 shows a horizontal line at -40°F that terminates with arrow heads labeled A and B. What the diagram tells us is that this 5 % solution at -40°F is a mixture of solid ice having composition A (about 0.7 % salt*) and liquid water having composition B (about 28.3 % salt). Hence, it tells us we have a slush (a water-ice mixture) and it tells us the compositions of the ice and water in the slush. A solution corresponding to any point in the shaded slush region of the phase diagram is going to be a slush, consisting of a mixture of water with ice. Hence, each region on the phase diagram tells us what phases, in this case solid or liquid, are present. If we are in the 2-phase region (the shaded slush region) it also tells us the composition of each of the 2 phases once we pick a temperature. However, if we are in the 1-phase solid or 1-phase liquid region it does not tell us the composition of the phase once we pick the temperature. It only tells us that we must have all solid or all liquid. In these cases the compositions are the overall average composition that you started with, a number not predicted by the phase diagram.

Summary of major ideas of chapter 2.

- 1 A liquid ***solution*** occurs when a substance dissolves in a liquid, such as salt into water. A solid solution is similar, like when salt dissolves in ice.
- 2 The stuff that dissolves into solution (salt in salt solutions, carbon in steel) loses its identity and is hidden from view as its atoms become incorporated into the solution.
- 3 Solutions have the same molecular structure or atomic structure from point to point within themselves. Each solution is called a ***phase***.
- 4 A phase diagram is a map having coordinates of temperature on the vertical axis and composition or concentration on the horizontal axis. The phase diagram map identifies those temperature-composition coordinates where a certain phase will exist.
- 5 A phase diagram also maps out temperature-composition coordinates where only phase mixtures can exist. For example on the Fig. 2.2 phase diagram the shaded slush region locates where slush mixtures of solid ice and liquid water exist.

* The real value is much less than 0.7%. The value was increased so it would be clear on the diagram.

3 - Steel and the Fe-C Phase Diagram

Steel is made by dissolving carbon into iron. Pure iron melts at an extremely high temperature, 2800 °F (1538 °C), and at such temperatures carbon readily dissolves into the molten iron generating a liquid solution. When the liquid solution solidifies it generates a "solid solution", in which the C atoms are dissolved into the solid iron. The individual C atoms lie in the holes between the iron atoms of the crystalline grains of austenite (high temperatures) or ferrite (low temperatures). If the amount of C dissolved in the molten iron is kept below 2.1 weight percent we have steel, but if it is above this value we have cast iron. Although liquid iron can dissolve C at levels well above 2.1%, solid iron cannot. This leads to a different solid structure for cast irons (iron with total %C greater 2.1%) which is discussed in more detail in Chapter 16.

In addition to C all modern steels contain the element manganese, Mn, and low levels of the impurity atoms sulfur, S, and phosphorous, P. Hence we can think of steels as an alloy of 3 or more elements given as Fe + C + X, where Fe and C are the chemical element symbol for iron and carbon, and X can be thought of as 3rd element additions and impurities. In the United States most steels are classified by a code developed by the American Iron and Steel Institute (AISI). It is customary to partition steel compositions into 2 categories, plain carbon steels and alloy steels. In plain carbon steels, X consists only of Mn, S and P, whereas in alloy steels one or more additional alloying elements are

Table 3.1 Composition (weight %) of some steels

Steel Type	American Iron&Steel Institute code (AISI number)	%C	%Mn	% Other	%S	%P
Plain carbon	1018	0.18	0.75	-	0.05 (max)	0.04 (max)
	1095	0.95	0.40	-	"	"
Alloy	5160	0.60	0.82	0.8 Cr	"	"

added. Table 3.1 lists the composition of 2 common plain carbon steels and one sees that the amount of C (in weight %) is related to the last 2 numbers of the code. The Mn level is not related to the code and must be looked up in a table. The first 2 numbers of the code, 10, identify the steel as a plain carbon steel. These 2 numbers are changed for alloy steels, and the table lists one example for a chromium (Cr) alloy steel. The alloy steels will be discussed in more detail later.

Solid solutions are similar to the liquid salt solution discussed in the last chapter, in that, after the substance has become dissolved its presence is no longer evident to an observer as it had been previous to the dissolving. This may be illustrated for steel as shown in Fig. 3.1. On the left one has a starting condition of a round iron containing only 3 grains. The iron is surrounded by a thin layer of graphite and heated to 1832 °F (1000 °C). After a period of several hours the graphite layer disappears. The C atoms of the graphite have migrated into the solid iron by a

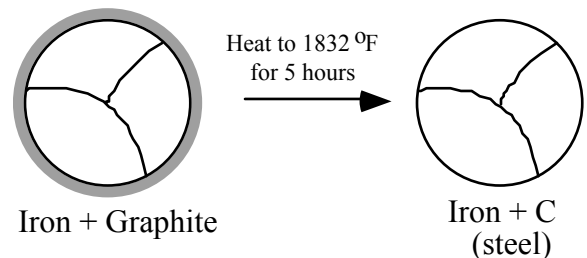


Figure 3.1 Converting a rod of iron containing only 3 grains to steel by dissolving carbon in it.

process called diffusion which is discussed in Chapter 7. All of the C atoms have fit themselves into the holes that exist between the iron atoms of the FCC austenite present at this temperature. This solid solution of C in Fe is steel.

Figure 1.3 locates the center of the iron atoms in the FCC lattice. Allow each of the little dots of Fig. 1.3 to expand until they touch each other and you end up with the model of FCC iron shown in Fig. 3.2. The expanded iron atoms touch each other along the face diagonals of the cube. The small open circles locate the center of the void spaces between the iron atoms. If you expand these small circles until they touch the iron atoms you find that their maximum diameter equals 41.4 % of the iron atom diameter. This means that X atoms smaller than around 42% of the iron atom diameter should fit into the holes between the iron atoms. Carbon atoms are small, but the diameter of carbon atoms is estimated to be 56 % of the diameter of iron atoms in austenite. Hence, when C dissolves in iron it pushes the iron atoms apart a small amount. The more carbon dissolved the further the iron atoms are pushed apart. Hence there is a limit to how much C can dissolve in iron.

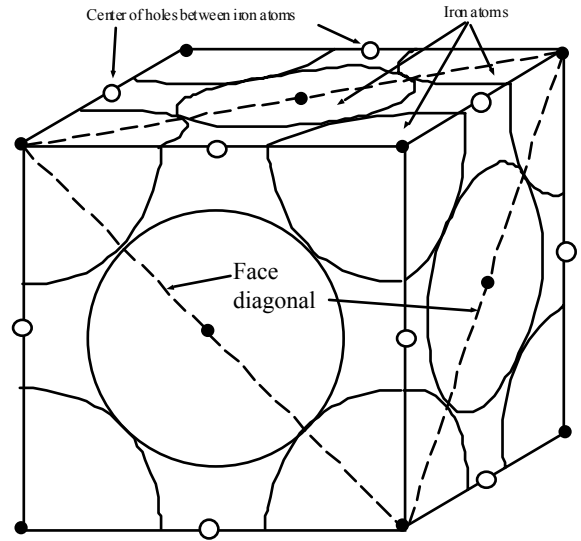


Figure 3.2 Location of iron atoms in FCC austenite. Small circles locate centers of holes between the iron atoms.

Historical Note: The iron age dates to around 1000 BC, when our ancestors first learned to reduce the plentiful iron oxide ores found on earth into elemental iron. The iron was made in furnaces that were heated by charcoal fires that were not able to get hot enough to melt the iron. They produced an iron called bloomery iron which is similar to modern wrought iron. Even though charcoal was used in these furnaces, very little carbon became dissolved in the iron. So, to make steel, carbon had to be added to the bloomery iron. (Even to this day steel cannot be economically made directly from the iron ore. The modern 2 step process first makes high carbon pig iron and the second step reduces the carbon composition to the steel range.) Our ancestors did not know the nature of the element C until around 1780-90AD, and steel and cast iron played a key role in its discovery. Until shortly before that time, the production of steel was primarily the result of blacksmiths heating bloomery iron in charcoal fires. This process is tricky as a charcoal fire can just as easily remove C as add it (see p. 63). Therefore, steel was made on a hit and miss basis from the start of the iron age, and the quality of such steel varied widely. The successful blacksmiths guarded their methods carefully.

In pure iron the difference in ferrite and austenite is a difference in their atomic structure. As illustrated in Figs. 1.2 and 1.3, the iron atoms are arranged with a BCC crystal structure in ferrite and a FCC crystal structure in austenite. In both ferrite grains and austenite grains this atomic structure does not change as one moves around in the grain. Hence, similar to ice and water of the last chapter, both ferrite and austenite are individual *phases*.

When C is added to austenite to form a solid solution, as illustrated above in Fig. 3.1, the solid solution has the same FCC crystal structure as in pure iron. As discussed with reference to Fig. 3.2, the C from the graphite just fits in-between the iron atoms. The crystal structure remains FCC, the only change being that the iron atoms are pushed

very slightly farther apart. Pure austenite and austenite with C dissolved in it are both the same phase. Hence, austenite with C dissolved in it, and ferrite with C dissolved in it are two different phases, both of which are steel.

Low Carbon Steels (Hypoeutectoid Steels)

The Fe-C phase diagram provides us with a temperature-composition map that tells us where on this map the two phases, austenite and ferrite, will occur. It also shows us where on the map we can expect to get mixtures of these 2 phases, just like the slush region on the ice-salt phase diagram. A portion of the Fe-C phase diagram is shown on Fig. 3.3 and it seen that there is a strong similarity to the salt diagram of Fig. 2.2. In pure iron, austenite transforms to ferrite on cooling to 912 °C (1674 °F). This transition temperature is traditionally called the A_3 temperature and the diagram shows that, just as adding salt to water lowers the freezing point of water, adding C to iron lowers the A_3 temperature. Whereas, the maximum lowering occurs at what is called the eutectic point in water-salt, a similar maximum lowering occurs in Fe-C, but here it is called the **eutectoid** point, and also, the **pearlite** point. The eutectoid point has a composition of 0.77 % C and steels with compositions less than this value are called **hypoeutectoid** steels, as illustrated in the title of Fig. 3.3. The eutectoid temperature is traditionally called the A_1 temperature.

Steels that are 100 % austenite must have temperature-composition coordinates within the central upper dark area of Fig. 3.3. Steels that are ferrite must have temperature composition coordinates in the skinny dark region at the left side of Fig. 3.3. The maximum amount of C that will dissolve into ferritic iron is only 0.02 %, which occurs at the eutectoid temperature of 727 °C (1340 °F). This means that ferrite is essentially pure iron because it is always 99.98% or purer with respect to C. Notice however, that austenite may dissolve much more carbon than ferrite. At the eutectoid temperature austenite dissolves 0.77 % C, which is roughly 38 times more C than ferrite will hold at this temperature. Austenite holds more C than ferrite because the holes between iron atoms are larger in the FCC structure than the BCC structure.

Remember that in the salt-water phase diagram the shaded slush region mapped the temperature composition points where one obtains slush: a mixture of the water and ice. Similarly, the central shaded region labeled $\alpha+\gamma$ of Fig. 3.3 maps temperature-composition points where steel consists of a mixture of ferrite and austenite. Suppose your were able to utilize a hot stage microscope to look at a polished steel having a

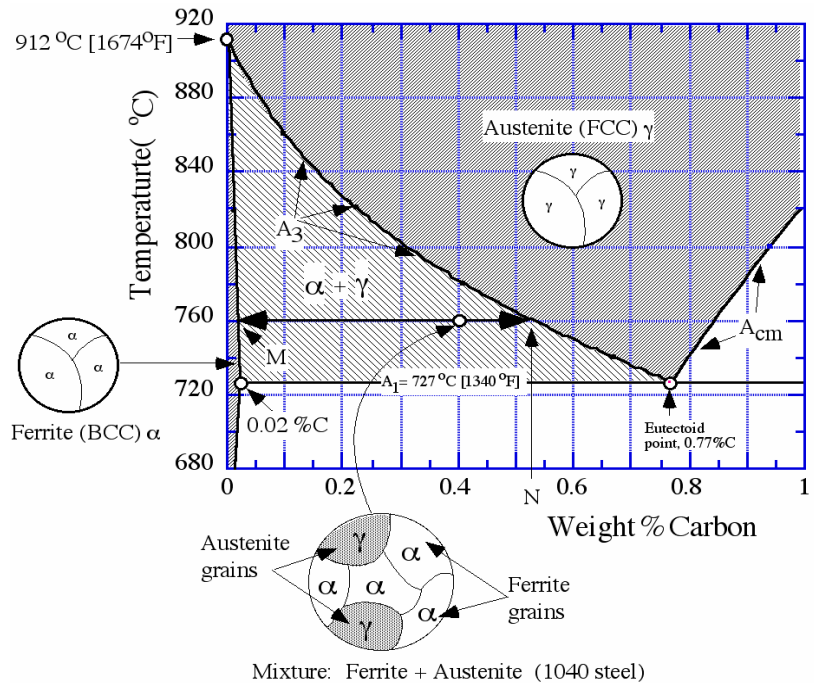


Figure 3.3 Portion of Fe-C phase diagram for hypoeutectoid alloys. (%C less than 0.77%)

composition of 0.4 % C after it was heated to 760 °C (1400 °F). Since this temperature-composition point lies in the central shaded region labeled $\alpha+\gamma$, the steel must be a mixture of ferrite and austenite. What you would observe would be a mixture of ferrite grains and austenite grains, as shown at the bottom of Fig. 3.3. The phase diagram also tells you information about the composition of the two phases. The austenite grains must have the composition given as N, and the ferrite the composition given as M on Fig. 3.3.

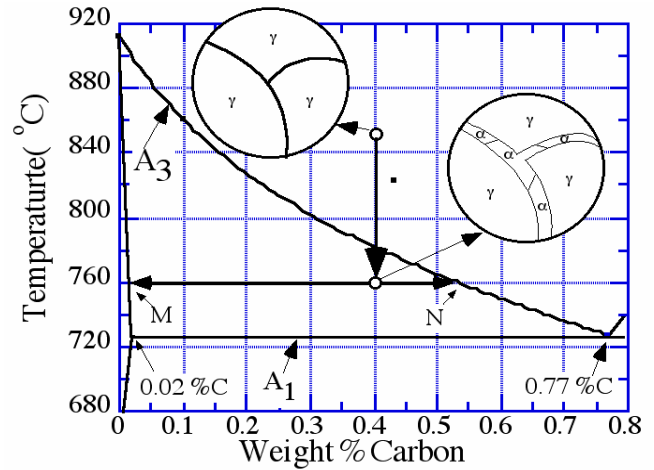


Figure 3.4 Change in microstructure on cooling a 1040 steel from 850 °C to 760 °C.

As a further illustration of the usefulness of the phase diagram consider the following simple experiment. A steel of composition 0.4 %C is first heated to 850 °C (1562 °F) and held for around 10 minutes. After this short hold all the grains in this steel would consist of pure FCC austenite grains with a composition of 0.4 % C. To make the illustration simple image that we are looking at the steel in a hot stage microscope and we see a region of only 3 grains as shown on Fig. 3.4. Now the hot stage temperature is reduced to 760 °C (1400 °F) and the sample slowly cools to this temperature. What happens to the microstructure? The phase diagram tells us that after cooling the steel must become 2-phase, a mixture of austenite and ferrite. Experiments show that the ferrite that forms in the pure austenite as it cools virtually always forms on the austenite grain boundaries. This is illustrated in the lower microstructure of Fig. 3.4, where the ferrite has formed as a number of α grains along the prior austenite grain boundaries. Comparing the microstructure at the right side of Fig. 3.4 to that at the bottom of Fig. 3.3, one sees similarities and differences. They are similar in that both contain a mixture of ferrite and austenite grains with the same volume fraction of each. But they are different in that the distribution of the ferrite grains is quite different. The microstructure of Fig. 3.3 will generally be formed upon heating the steel from room temperature up to 760 °C (1400 °F). Hence, this example illustrates one of the fascinating aspects of steels, the microstructure is controlled by heat treatment. As we will show later, the mechanical properties of steels are controlled by microstructure. The **microstructure** of a steel generally refers to the specific shape, size, distribution, and phase types of the grains in the steel. Remember, the phases present in Figs. 3.3 and 3.4 are only present at the high temperature of 760 °C (1400°F), not at room temperature. We will discuss room temperature phases later.

High Carbon Steels (Hypereutectoid Steels)

As the %C dissolved in austenite increases the iron atoms are pushed further apart. This stretches the chemical bonds that hold the Fe atoms together generating a form of energy called strain energy. There is a limit to how much strain energy the austenite can stand. The amount of C dissolved in austenite when this limit is reached is called the solubility limit. Question: The solubility limit in austenite at 820 °C [1508 °F] is 1 wt. %C. If you make up an alloy containing 1.5 wt. % C and heat it to 820 °C, only 1% of this 1.5 %C will be dissolved in the austenite; what happens to the remaining 0.5 %C? This excess C becomes

incorporated into a new phase called cementite. The new phase, cementite, has one major difference from austenite or ferrite. It is a chemical compound that exists at only 1 composition. Chemical compounds are generally represented by their elemental formulas, such as NaCl, for sodium chloride table salt. The 1 composition for NaCl is 50 atomic percent sodium, which corresponds to 39.3 weight percent sodium. The chemical element formula for cementite is Fe_3C . For each atom of C in the compound there are 3 atoms of iron, giving an atomic composition of 25 at. % C. The corresponding weight percent carbon in cementite turns out to be 6.7 wt. %C. Other than this limitation to 1 composition, cementite has several similarities to austenite and ferrite. It is a crystal having its atoms arranged in regularly repeating geometrical arrays. The crystal structure is a bit more complex than either BCC of ferrite or the FCC of austenite, but it is well known. Also it is a separate phase and is present as discrete grains. So the excess 0.5 %C in our steel at 820 °C [1508 °F] will all be present as separate cementite grains mixed in with the austenite grains, i.e., the microstructure will be a 2-phase mixture of austenite and cementite.

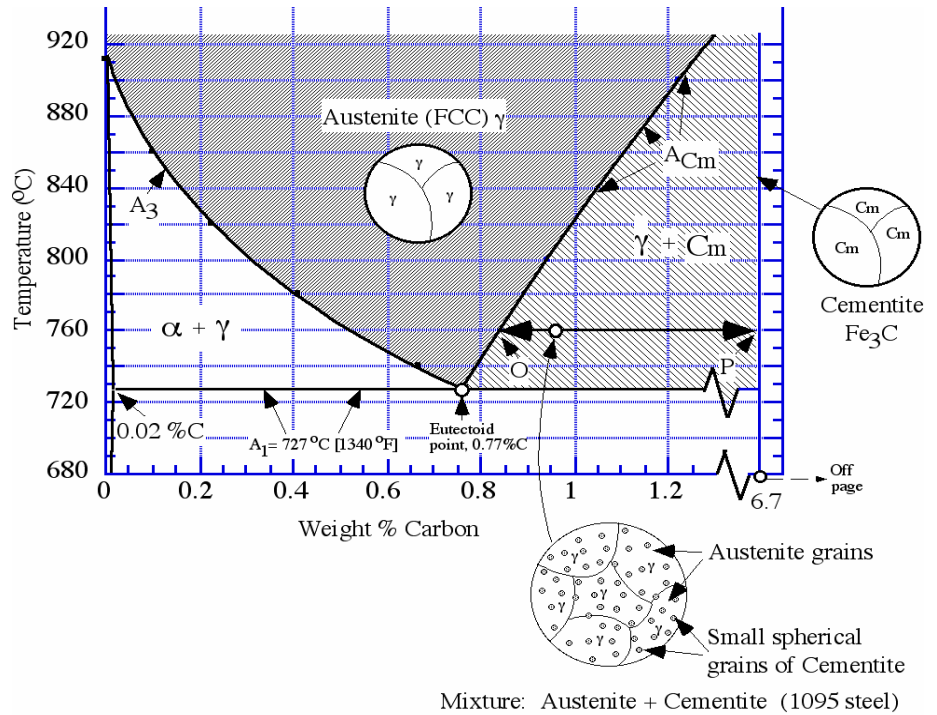


Figure 3.5 Extension of the Fe-C phase diagram to hypereutectoid alloys, (%C greater than 0.77 %).

The Fe-C phase diagram extended to higher carbon compositions where cementite becomes important is shown in Fig. 3.5. As before, the region on the temperature-composition map corresponding to austenite is shown as the central dark region. Because cementite exists at only 1 composition, it is shown on the phase diagram as a vertical line located at its 1 composition, 6.7 %C. Notice that the composition axis at the bottom of the diagram has a break in it just beyond 1.2 % and the value of 6.7 % is located next to the break. If the break were not inserted the 6.7 % composition would appear roughly 1 foot to the right. To envision the true diagram in your mind you simply need to extend the right portion over about 1 foot, which expands the shaded 2-phase region labeled $\gamma + \text{Cm}$ into a much large area.

The line on the diagram labeled A_{cm} defines the solubility limit for C in austenite. Notice that at 820 °C this line gives a point at 1 wt. %C, which is the maximum amount of C that can be dissolved in austenite at 820 °C [1508 °F]. Alloys having % C values to the right of the A_{cm} line are in shaded 2-phase region labeled $\gamma + \text{Cm}$ and must consist of a mixture of austenite and cementite grains. Consider a 1095 steel (0.95 wt. %C)

received from a steel mill. If this steel is heated to 760 °C [1400 °F] it will be at the open circle point located on the diagram with the horizontal arrowed line passing through it. Because the temperature-composition point now lies in the shaded 2-phase region labeled $\gamma + \text{Cm}$, we know that this steel must consist of a mixture of austenite having composition O (0.85 %C) and cementite of composition P (6.7 %C). The diagram does not tell us what the microstructure will look like. Experiments show that the microstructure will be as shown on the bottom of Fig. 3.5. All of the cementite is found to be present as small spherically shaped grains distributed fairly randomly over the austenite grains which have much larger sizes and are present with the typical curved grain boundaries.

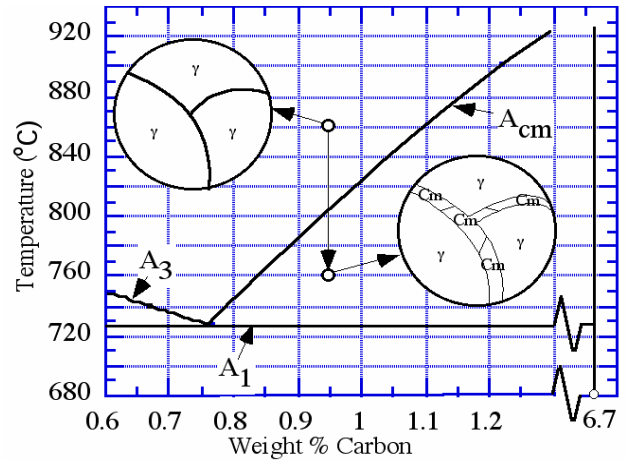


Figure 3.6 Change in microstructure on cooling a 1095 steel from 900 °C to 760 °C.

To further illustrate the use of the phase diagram in understanding how microstructure changes during heat treatment, consider an experiment where the as-received 1095 steel is heated to 850 °C [1562 °F], and held for 20 minutes or so. As shown on the phase diagram of Fig. 3.6 this temperature-composition point corresponds to the single phase austenite region. Assuming we could observe the structure in a hot stage microscope the small region under observation at high magnification might consist of just 3 grains, which would have an appearance similar to that shown on Fig. 3.6. The temperature of the hot stage is now lowered to 760 °C [1400 °F] and this temperature-composition point lies in the 2-phase austenite + cementite region. This means that cementite grains must form on cooling. Just as is the case for hypoeutectoid steel of Fig. 3.3, where ferrite forms on the cooling austenite grain boundaries, here cementite forms on the austenite grain boundaries during cooling. As shown on Fig. 3.6, one ends up with a microstructure in which all of the prior austenite grain boundaries from the 850 °C structure are filled with thin plate shaped grains of cementite. Notice the dramatic difference in this microstructure from that shown on Fig. 3.5 where the 1095 steel was heated directly from room temperature to 760 °C. Both microstructures contain the same volume fraction of cementite and austenite but the distribution of the cementite is quite different. Unlike austenite and ferrite, cementite is very brittle. Consequently the 1095 structure of Fig. 3.6 with its interconnected Cm plates is not as tough as the Fig. 3.5 structure with its small isolated Cm grains. Again, this is an example of how heat treatment can change microstructure which in-turn changes mechanical properties.

Eutectoid Steel (Pearlite)

In the previous 2 sections we considered steels having compositions on either side of the eutectoid composition of 0.77 wt. %C. It turns out that steels having the composition of 0.77 %C (a 1077 steel) generate a unique microstructure that is called pearlite. Figure 3.7 presents the Fe-C phase diagram on which the area below the A_1 line of 727 °C [1340 °F] is shaded dark. This entire area is a 2-phase region. Any steel cooled slowly into the temperature-composition coordinates of this area must consist of a mixture of the 2 phases: ferrite and cementite ($\alpha + \text{Cm}$). The

microstructures of steels in this 2-phase region vary widely and pearlite is just one of many microstructures that can occur.

To understand the pearlite microstructure consider a 1077 steel that is heated in a hot stage microscope to 800 °C [1472 °F]. As shown on Fig. 3.7 the steel will consist of all austenite grains after just a minute or two at 800 °C. After cooling to a temperature below A_1 , and holding for 5 to 10 minutes or so, the austenite grains will be completely replaced by a new set of pearlite grains, as shown on the figure. Contrary to all the grains we have discussed up to this point, the pearlite grains are not a single phase. Rather, they consist of a mixture of 2 phases, $\alpha + C_m$, having a unique microstructure. To observe the true details of the microstructure, one must blow up a small region within a pearlite grain to a very high magnification, as shown on the lower right of Fig. 3.7. The structure consists of alternating plates of ferrite and cementite. The ferrite plates are much fatter than the cementite plates, occupying 90 % of the volume compared to only 10 % for the cementite. At the pearlite grain boundaries one observe an abrupt change in the orientation of the plates as is shown for a real sample in Fig. 3.8, which is a transmission electron microscope picture at a magnification of 11000x. In this picture the cementite plates are the light phase and the ferrite plates are the dark phase. (Note that the C_m plates are only 0.1 μm thick, too thin to be resolved on an optical microscope. Although C_m is brittle pearlite is not, due largely to the fine size of the C_m plates.)

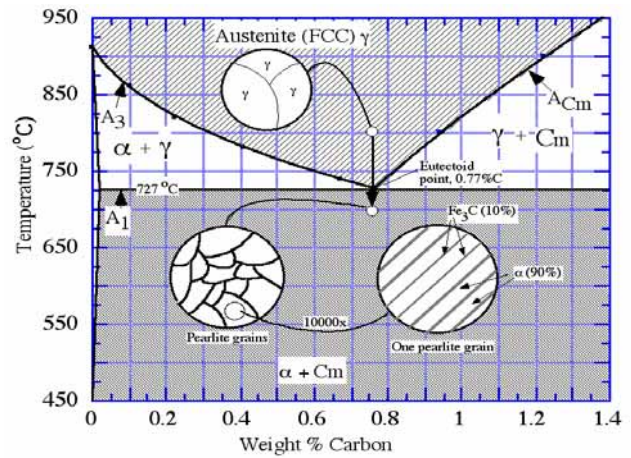


Figure 3.7 Formation of the pearlite microstructure on cooling a 1077 steel below the A_1 temperature of 727 °C [1340 °F].

If the 1077 steel is now cooled from the 700 °C temperature shown on Fig. 3.7 to room temperature, the microstructure will not change significantly no matter how slow or fast the sample is cooled. The ferrite will remain a nearly pure BCC iron with less than 0.02 %C dissolved in it and the cementite will remain at 6.7 %C with an unchanged crystal structure. The phase diagram tells us that once austenite is cooled below the A_1 temperature and held for a short period, the austenite will be completely replaced by some form of $\alpha + C_m$ and on cooling to room temperature no further changes in the resulting $\alpha + C_m$ microstructure will occur. When we look at plain carbon steels at room temperature we never see austenite.* This means that microstructures containing austenite, such as those shown on Figs 3.2 to 3.5, can only be seen in a hot stage microscope, because the austenite will be replaced by other structures on cooling. At high cooling rates these include the martensite and bainite structures discussed below. At air cooling rates and slower the austenite will transform into some form of $\alpha + C_m$.

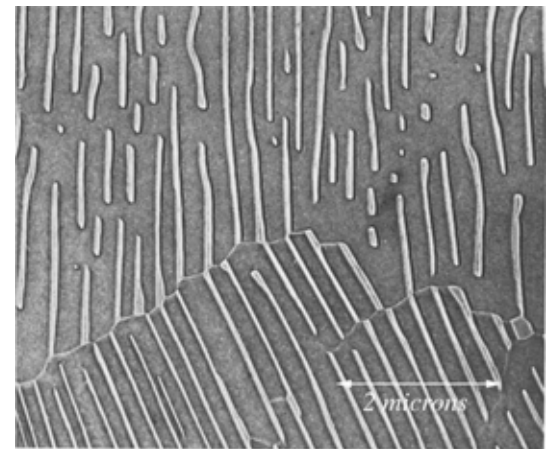


Figure 3.8 An electron microscope image of pearlite after polishing and etching in nital. Magnification = 11000x [3.1]

* An exception to this rule is quenched high carbon steels, which contain mixtures of martensite and retained austenite.

The A_1 , A_{e1} , A_{c1} , A_{r1} Nomenclature The Fe-C phase diagram shown in the above figures is called an *equilibrium* phase diagram. This means that the transformation temperatures given by the A lines were determined at extremely slow cooling or heating rates where equilibrium conditions are obtained. The A_3 , A_{cm} , and A_1 lines that appear on equilibrium phase diagrams are often labeled the A_{e3} , A_{ecm} and A_{e1} lines respectively, where the e indicates equilibrium conditions. In this book the e will generally not be used. The absence of e implies equilibrium conditions.

Consider again the experiment illustrated on Fig. 3.7. The diagram predicts that when the austenite grains cool to 727 °C [1340 °F], pearlite will start to form from the austenite. This only occurs if one cools the austenite extremely slowly. At even modest cooling rates like 5 °F/min. (2.8 °C/min.) the transformation temperature is lowered by around 20 °C (36 °F). This means that the Fe-C diagram can only be used as a rough guide for estimating transformation temperatures. Not only is the transformation from austenite to pearlite on cooling shifted down in temperature, the reverse transformation from pearlite to austenite on heating is shifted up in temperature. To give you an idea of the magnitude of this shift on cooling and heating and how it can be measured, a simple experiment was run. A hole was drilled in a small piece of 1018 steel and a thermocouple secured in the hole. The output of the thermocouple was measured with a digital voltmeter every 2 seconds and sent to a pc where it was converted to a file of temperature versus time. The sample was placed in a small resistance furnace and heated to 870 °C [1598 °F] and then removed from the furnace. The output of the thermocouple for both the heating and cooling cycle is shown on Figs. 3.9 and 3.10.

As explained in Chapter 1, when austenite changes to ferrite on cooling heat is liberated and when ferrite changes to austenite on heating heat is absorbed. Consider first the heating curve of Fig. 3.10. As we will discuss in Chapters 5 and 7, the A_3 and the A_1 lines of the pure Fe-C diagram are shifted down in temperature by the 0.75 % Mn and 0.2 % Si present in 1018 steel to the values of $A_1 = 725$ °C, and $A_3 = 824$ °C. The heating data of Fig. 3.10 show that at around 737 °C the rate of temperature rise abruptly decreases. This is due to the heat absorbed by the sample as the pearlite part of the steel transforms to austenite. It means that the A_1 line has shifted up by 12 °C, from 725 to 737 °C. It is customary to label the actual temperature of the transformation on heating A_{c1} , as shown on the figure. The amount of the upward shift depends on the heating rate. If the heating rate were increased above the value of 40 °C/min. the value of A_{c1} would increase. On cooling an opposite effect occurs, the heat liberated when austenite transforms to ferrite or to pearlite slows down the rate of decrease in the sample temperature. Figure 3.9 illustrates this effect for both the austenite \Rightarrow ferrite transformation below the A_3 temperature and the austenite \Rightarrow pearlite transformation below the A_1 temperature. The former transformation begins to occur here at 762 °C, which is 62 °C below the A_3 temperature of 824 °C and the latter occurs at 652 °C which is 73 °C below the A_1 temperature of 725 °C. As shown on Fig. 3.9 it is customary to label the actual transformation temperatures that occur on cooling the A_{r3} and A_{r1} temperatures. Notice that the cooling rate for the data of Fig. 3.9 is 3 times larger than the heating rate for the data of Fig. 3.10. This larger rate accounts for the increased shift

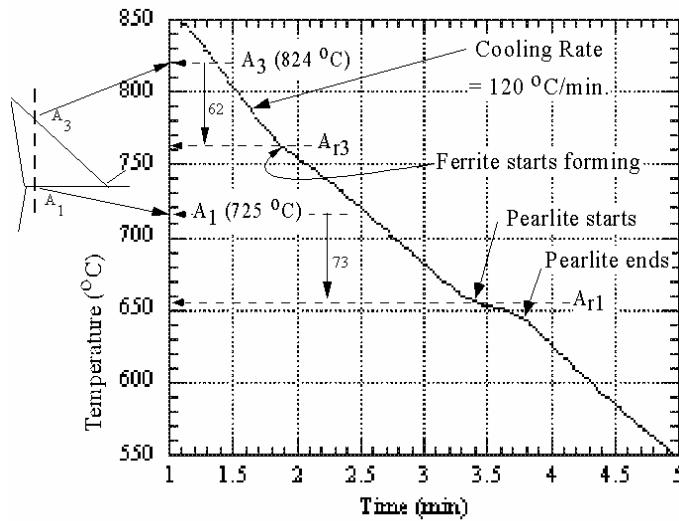


Figure 3.9 Cooling (refroidissement) curve for a 1018 steel.

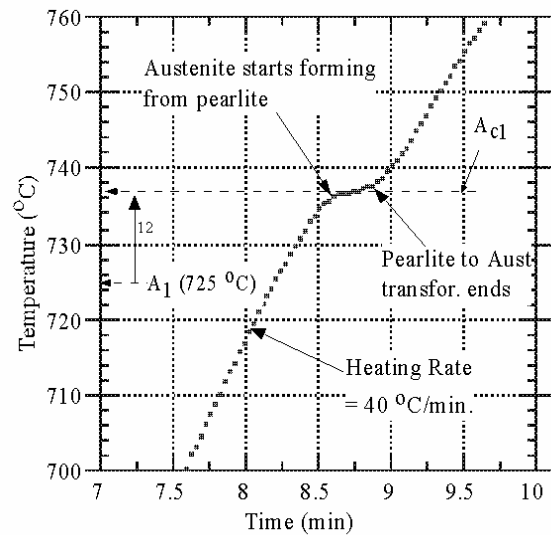


Figure 3.10 Heating (chauffage) curve for a 1018 steel.

in the A_1 temperature from $-73\text{ }^{\circ}\text{C}$ on cooling to only $+12\text{ }^{\circ}\text{C}$ on heating. (The temperature range of Fig. 3.10 did not extend high enough to measure the increased A_3 temperature, which is called the A_{c3} temperature.)

Historical Note: The same French scientist, Floris Osmond, who is responsible for the name of martensite is also responsible for the use of the letters r and c for the shift in the A lines on cooling and heating. At the end of the 19th century he was the first scientist to use thermocouples to measure the effect of heating and cooling rates. The letter r is from the French word for cooling, refroidissement, and the letter c is from the French word for heating, chauffage.

Figure 3.11 presents a graphical summary of the above ideas showing the shift up of the A lines on heating with labels having subscript c added, and the shift down on cooling with the labels have the subscript r added. These shifts in transformation temperatures can become important in operations involving rapid heating and cooling. An example is the shift up in transformation temperature with heating in processes such as flame and induction hardening.

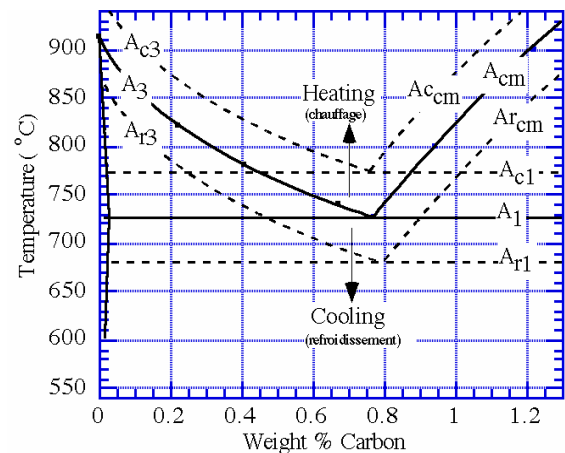


Figure 3.11 Nomenclature for the A lines shifted up on heating and down on cooling.

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- 3.2 Heat Treaters Guide, 2nd Edition, ASM International, Materials Park, Ohio (1995).