HEAT TREATMENT OF STEEL
Background Unit: Heat Treatment of Steel

Introduction

Figure 1 shows a slightly simplified version of the Fe-Fe₃C alloy system. (The simplification consists of ignoring complex freezing behavior between 0% C and 0.53% C and between 1394°C and 1538°C. This behavior arises from the formation of δ, delta, the high-temperature body centered cubic form of iron, which is ignored here. Since all steels will pass through the single-phase austenite (γ, gamma) region and the heat treatment of steel is concerned with the conversion of γ to other phases at lower temperature, ignoring the δ-iron isn’t too serious. Four phases occur on the diagram in Fig. 1:
1. liquid, L, by itself at all temperatures above the liquidus, and mixed with a solid phase at temperatures between the liquidus and solidus.
2. austenite, γ, the solid solution of carbon with FCC γ iron.
3. ferrite, α, the solid solution of carbon with BCC α iron.
4. cementite, Fe₃C, or iron carbide, a compound of iron and carbon.

Notice that austenite can dissolve much more carbon than ferrite. Especially notice that at 727°C the ferrite can dissolve only 0.02% C while the austenite can dissolve 0.77% C. The Fe-Fe₃C phase diagram is the basis of steels and cast irons. Plain carbon steels contain up to 2.11% C and cast irons contain more than 2.11% C.

Figure 1 – Iron – Iron Carbide System
Objectives

After studying this unit and completing the lab assignment you should be able to complete the following tasks:

1. Write complete definitions of the following terms:
   a. austenite  e. hardening, or quenching
   b. ferrite     f. tempering, or drawing
   c. cementite  g. plain carbon steel
   d. martensite h. eutectoid reaction

2. Given the Fe-Fe₃C phase diagram, determine the following for a steel of any carbon content:
   a. The temperature at which austenite first starts to decompose on slow cooling and the names of the decomposition products.
   b. The names and carbon contents of the constituents in the microstructure of a slowly cooled steel.
   c. The relative proportions of the constituents in the microstructure if the steel is slowly cooled.
   d. The names and the carbon contents of the phases in the microstructure if the steel is slowly cooled.
   e. The relative proportions of the phases in the microstructure if the steel is slowly cooled.

3. Discuss the hardening of steel including the nature of the hardening reaction, the reason quenching is necessary, the purpose of alloying elements in steel, the tempering reaction and its purpose, and the effect of carbon content on the hardness of quenched steels.

4. Given a tensile bar of a standard low-alloy steel, successfully harden it by oil quenching.

5. Discuss the role of the quenching step in hardening steels. What microstructure is produced by quenching? Why aren't steels used in the as-quenched condition?

6. Discuss the role of the tempering step in hardening steels. What microstructure is produced by tempering? What's the effect of tempering temperature on the strength, ductility, hardness, and modulus of a quenched steel?

7. Given a microstructure of an annealed or hardened steel identify which condition the steel is in and also identify the constituents.

Slowly Cooled Steels

Before you can understand the processes which occur when the steel is quenched (rapidly cooled from the austenite region), you need to understand the processes which occur when the steel is slowly cooled. In this unit we are concentrating on plain carbon steel, an alloy of iron and carbon only. Steels contain less than 2.11% carbon: steels are defined as those Fe-C alloys which can be heated into the single phase austenite region at some temperature. Cast irons contain more than 2.11% C, but also usually contain substantial amounts of silicon which makes their behavior more complex.
Let’s start by considering a 0.77% C steel. This relatively high carbon steel would be a plain carbon tool steel such as would be used to make cutlery.

On cooling, this 0.77% C steel becomes single phase austenite at about 1400°C. Notice that no other changes occur as this steel is cooled to 727°C. But at just above 727°C the 0.77% C steel is in the single phase austenite region while at just below 727°C it is in a two phase region.

Clearly the following reaction must occur at 727°C:

\[
\text{Austenite (}.77\% \text{ C)} \xrightarrow{727\, ^\circ\text{C}} \text{Ferrite (0.02\% C) + cementite (6.67\% C)}
\]

\[
\gamma \rightarrow \alpha + \text{Fe}_3\text{C}
\]

This reaction forms two solid phases, \( \alpha \) and \( \text{Fe}_3\text{C} \), from one phase, \( \gamma \). This is reminiscent of the eutectic reaction which formed two solid phases from one liquid phase on cooling. The above reaction is one of a large class of reactions called eutectoid reactions. Of course, 727°C is the eutectoid temperature. 0.77% C is the eutectoid composition, and the horizontal line at 727°C is the eutectoid horizontal.

When austenite decomposes to ferrite plus cementite by the eutectoid reaction, the product phases are arranged in a very characteristic pearlite pattern; the cementite is in the form of plates in a matrix of ferrite. \{Fig. 2. Actually both the cementite and ferrite are a light color; the cementite is shaded here for contrast.\} This particular pattern of cementite and ferrite is called pearlite. In etched steels at low magnifications the pearlite is black, only at very high magnifications can the plates of cementite be resolved. Pearlite is an example of a microstructural constituent that has two phases. When viewed at moderate magnifications the pearlite appears distinct from other constituents, but the two phases cannot be resolved until higher magnifications are used. Each constituent is formed by a distinct process on cooling; the pearlite is formed by the eutectoid decomposition of austenite containing 0.77% C. Since the pearlite is formed from austenite containing 0.77% C, the carbon content of the pearlite must be 0.77% C.
Now consider a 0.3% C steel. This composition is typical of the carbon content of steels used for gears, shafts, etc.

For a 0.3% C steel slowly cooled through the eutectoid temperature:

At just above 727°C the tie line for the system is:

\[
\begin{array}{ccc}
\alpha & \text{Fe}_3\text{C} \\
\Delta C_a = 0.02 & \Delta C_o = 0.3 & \Delta C_{\text{Fe}_3\text{C}} = 6.67
\end{array}
\]

At just above 727°C there are two phases present:

- austenite at 0.77% C, relative proportion = 0.373 and
- ferrite at 0.02 % C, relative proportion = 0.627.

At 727°C the austenite decomposes to pearlite, but the ferrite that was already formed remains unchanged. This ferrite that was formed above the eutectoid temperature is called primary or pro-eutectoid ferrite.

At just below 727°C there are two constituents present:

- pearlite at 0.77% C, relative proportion = 0.373 (same as the austenite above 727°C)

and

- primary ferrite at 0.02% C, relative proportion = 0.627.

The microstructure of the 0.3% C steel is sketched in Fig. 3. The microstructure shows the distinctly appearing constituent regions: the dark pearlite formed at 727°C and the large, light areas of primary ferrite formed above 727°C as the steel cooled through the austenite + ferrite field. Since at 727°C the austenite of 0.77% C changes into pearlite, the pearlite will contain 0.77% C and will be present in the same relative proportion as the austenite at just above 727°C. Of course, the ferrite in the pearlite is just the same chemically and physically as the primary ferrite.

The slight composition change which occurs from just below 727°C to room temperature as the solubility of carbon in ferrite decreases from 0.02% to virtually zero isn't too important. The important lever law calculations for the phases and constituents in a 0.3% C steel at room temperature are as follows:

\[
\begin{array}{ccc}
\text{pearlite} & \alpha & \text{primary ferrite} \\
\approx 100 \times
\end{array}
\]

\text{Slowly Cooled .3% C Steel}

\text{Figure 3}
Relative proportions of phases at room temperature, 0.3% C steel:

\[
\begin{align*}
\Delta C_{\text{ferrite}} &= 0.00 \\
\Delta C_o &= 0.3 \\
\Delta C_{\text{cementite}} &= 6.67 \\
\end{align*}
\]

R.P. Fe\textsubscript{3}C = \frac{0.3 - 0.00}{6.67 - 0.00} = 0.045

R.P. α = \frac{6.67 - 0.3}{6.67 - 0.00} = 0.955

check: 0.955 + 0.045 = 1.00

Relative proportions of constituents at room temperature, 0.3% C steel:

\[
\begin{align*}
\Delta C_{\text{primary ferrite}} &= 0.00 \\
\Delta C_o &= 0.3 \\
\Delta C_{\text{pearlite}} &= 0.77 \\
\end{align*}
\]

R.P. pearlite = \frac{0.3 - 0.00}{0.77 - 0.00} = 0.390

R.P. primary ferrite = \frac{0.77 - 0.30}{0.77 - 0.00} = 0.610

check: 0.390 + 0.610 = 1.00

**Hardening of Steel**

Steels are usually bought and machined in the slowly cooled (softened) condition; after hardening they are too hard for any usual form of machining except grinding. However, steels have a unique ability to be hardened if they are heated into the austenite region and quenched to a low temperature (like room temperature). This austenitizing operation requires forming a homogeneous solid solution of carbon dissolved in FCC iron.

Hardening results by cooling the steel so rapidly that pearlite or primary ferrite cannot form, but, instead, an entirely new phase, martensite, forms. Martensite is a metastable supersaturated solid solution of carbon in body centered tetragonal iron. Of course, the martensite will have the same carbon content as the austenite from which it is formed. Martensite does not appear on the equilibrium phase diagram for the Fe-Fe\textsubscript{3}C system because it is a metastable phase. The quenching reaction will be:

\[
\text{austenite} \xrightarrow{\text{quenching}} \text{martensite}
\]
The hardness of the as-quenched martensite depends almost entirely on the carbon content of the martensite; the higher the carbon content, the harder the martensite.

Successful formation of martensite depends on cooling the austenite so rapidly that the equilibrium constituents don’t have a chance to form. Since pearlite and ferrite tend to form very rapidly (a 0.4% C steel cooled to 550°C and held will begin forming pearlite within 0.5 seconds and will be completely transformed within 3 seconds), only relatively small pieces of plain carbon steels can be quenched rapidly enough to get martensite. The purpose of adding alloying elements like nickel, chromium, molybdenum, and boron to steels is not to make them harder but to slow down the ferrite and pearlite formation reactions, giving more time for martensite to form as the steel is quenched. Steels with small amounts of elements other than C or Fe added are called low-alloy steels. The compositions of steel are often identified with an AISI-SAE number (AISI is the American Iron and Steel Institute and SAE is the Society of Automotive Engineers). For instance, 4140 steel has 0.40 to 1.20% Cr, 0.08 to 0.25% Mo, and 0.40% C. These AISI-SAE numbers and compositions are tabulated in readily available sources.

As-quenched martensite is so hard it has almost no ductility. To get a usable material, we must trade-off some of the hardness gained by quenching to gain some toughness. We do this by reheating the quenched steel to some temperature below 727°C to allow the equilibrium phases, \( \alpha \) and Fe\(_3\)C, to form. This reaction will partially soften the steel resulting in a tougher, more ductile material than the as-quenched steel. This process is called tempering (the old name is "drawing"). When martensite is tempered the metastable supersaturated solid solution decomposes to form tiny spheres of iron carbide (visible only with an electron microscope) in a matrix of ferrite. The tempering reaction forms a new constituent, tempered martensite. Tempered martensite is composed of two phases, ferrite and cementite.

The tempering reaction:

- **constituents:** martensite \( \rightarrow \) tempered martensite
- **phases:** martensite \( \rightarrow \) \( \alpha \) + Fe\(_3\)C

or for a specific steel:

\[
\text{austenite (0.3\% C)} \xrightarrow{\text{quenching}} \text{martensite (0.3\% C)}
\]

or:

\[
\text{austenite (0.77\% C)} \xrightarrow{\text{quenching}} \text{martensite (0.77\% C)}
\]
Note that the same phases appear in tempered martensite as in pearlite, but tempered martensite and pearlite are distinctly different constituents. It is always important for us to know what phases are present and also to know what their arrangement is (what constituents are present).

1. Pearlite is formed by the eutectoid decomposition of austenite containing 0.77% C, while tempered martensite is formed by decomposing martensite (of any C content up to 2.11% C).
2. The Fe$_3$C particles in pearlite are parallel lamellae in a ferrite matrix, while the Fe$_3$C particles in tempered martensite are tiny spheres in a ferrite matrix.
3. Pearlite always has a carbon content of about 0.77% C, but the carbon content of tempered martensite is the same as that of the martensite from which it is produced, which is the same as that of the austenite from which the martensite was quenched.

In general, the higher the tempering temperature or the longer the tempering time, the tougher, softer, and weaker the tempered martensite will be. This is because there will be fewer, larger particles of Fe$_3$C (we don't add any C to the system so if some Fe$_3$C particles get larger, some have to dissolve). A steel that has been hardened is called a quenched and tempered (Q & T) steel. The following Table 1 emphasizes the control in properties which can be gained by controlling the distribution of the phases through heat treatment.

Table 1. Approximate Properties of 0.77% C Plain Carbon Steel

<table>
<thead>
<tr>
<th>Condition</th>
<th>Constituent</th>
<th>Strengths ($\times 10^3$ psi)</th>
<th>Hardness (BHN)</th>
<th>%El</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annealed</td>
<td>pearlite</td>
<td>54.0</td>
<td>89.0</td>
<td>174</td>
</tr>
<tr>
<td>Quenched &amp; Tempered at 400°F</td>
<td>tempered</td>
<td>152</td>
<td>216</td>
<td>601</td>
</tr>
<tr>
<td>(~ 205°C)</td>
<td>martensite</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quenched &amp; Tempered at 800°F</td>
<td>tempered</td>
<td>139</td>
<td>199</td>
<td>388</td>
</tr>
<tr>
<td>(~ 425°C)</td>
<td>martensite</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quenched &amp; Tempered at 1200°F</td>
<td>tempered</td>
<td>85</td>
<td>122</td>
<td>235</td>
</tr>
<tr>
<td>(~ 650°C)</td>
<td>martensite</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1.8 (temp. in °C) = (temp. in °F) – 32
Laboratory Unit: Heat Treatment of Steel

Introduction

In this laboratory unit you will heat treat a steel tensile test specimen by quenching and tempering it. You will also test the mechanical properties of two tensile test specimens of the same steel, one in the fully annealed condition and one in the quenched and tempered condition. Additionally you will examine and sketch the microstructure of annealed and hardened steels.

Experimental Procedure

Your group will be given 3 tensile test specimens of a hardenable steel, one in each of the following conditions:

1. fully annealed (furnace cooled from the $\gamma$ region)
2. quenched and tempered (quenched in on from the $\gamma$ region and tempered for 1 hour at 1000°F)
3. "as-received" (between normalized, air cooled from the $\gamma$ region, and annealed)

Hardness Testing

Measure the Rockwell hardness (use the B or C scale, as appropriate) of your steel in the following conditions:

a. as-received
b. fully annealed
c. as-quenched (before tempering)
d. quenched and tempered

Heat Treatment

You will harden the "as-received" specimen by heating it at the recommended hardening temperature (1550°F to 1600°F) for 1 hour, then quenching it in oil to room temperature. Your instructor will demonstrate oil quenching and provide safety instructions. As soon as possible after quenching begin tempering the specimen for 1 hour at 1000°F. After tempering it, since it will have transformed to the low temperature equilibrium phases, it can be slowly or rapidly cooled.

When you have completed the Q & T operation put the specimen in the cabinet so that another group can test it.

Tensile Tests

You will test the annealed and the quenched and tempered samples using the UTM with the electronic extensometer.

1. Using the hardness you measured predict the UTS and determine what range the UTM should be on.
2. Prepare and zero the UTM, load the specimen, connect the electronic extensometer, and make sure the data recording software is ready.

3. As you begin your test load very slowly until you are sure that the data are being recorded, then you can load at a slightly faster rate (between 8 and 12 on the "load" dial should be fast enough). Remove the extensometer when prompted to by the computer.

4. Take the data from the computer for analysis.

Microstructures

Metallographic specimens of steel similar to the one you are testing have been prepared. You will sketch an annealed, as-quenched, and quenched and tempered microstructure.

The annealed microstructure should show large, light colored proeutectoid ferrite areas and eutectoid constituent. The eutectoid constituent is pearlite. Pearlite is a lamellar mixture of ferrite and cementite formed from eutectoid decomposition of austenite. You may be able to distinguish the two phases if high enough magnification is used, but at lower magnifications the pearlite will appear as a dark gray.

The as-quenched microstructure is martensite. Martensite is composed of needle like grains formed from the shear transformation of FCC austenite to BCT martensite. The microstructure will appear as many small, randomly oriented, needle shaped grains.

The quenched and tempered microstructure will appear as a fairly homogeneous gray at most magnifications. Tempered martensite is composed of tiny spheres of Fe₃C in a ferrite matrix, however the cementite spheres are so small they cannot be distinguished without the aid of a very high power microscope.