Basic Heat Treating for Blacksmiths

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This program uses some basic metallurgical methods to explain what happens to the steel when we heat treat it. The program focuses on the process of austenitizing, quenching and tempering. It necessarily uses some terms and methods that may be unfamiliar to some of us. It is not intended that a person become a metallurgist to use them. These metallurgical tools are used to illustrate concepts like hardness, hardenability, cooling rates, etc. It is hoped that by understanding the basics of steel transformations, you can achieve better heat treating in the forge.
First, Some Terms

- Ferrite: iron at room temperature. Contains almost no carbon. Cubic crystal shape.
- Pearlite: ferrite with fingers of iron carbide arranged in parallel rows.
- Austenite: iron at 1330F or higher. Can contain lots of carbon. Cubic crystal shape.
- Martensite: iron that has been rapidly cooled from austenite. Can contain lots of carbon, tetragonal crystal shape.
- Bainite: Somewhat of a cross between ferrite and martensite.
Why Heat Treat?

- Iron alloys are among a small group of alloys that can be heat treated to higher strengths.
- Steel can be made harder, stronger and tougher by quench and tempering.
- Annealing makes steel softer and easier to form.
- Stress relieving removes residual stresses from forming operations.

There are many different heat treatments that can be applied to steel. We can make it softer, harder, more uniform, or just relieve stresses in the steel. Iron is one of the very few metals that can be dramatically changed by such a variety of heat treatments.

Definitions:

- **Anneal**: to heat to about 1200F-1300F, hold, and very slowly cool the steel to make it softer and easier to form, machine, or cut.
- **Normalize**: to heat to about 1750F, and cool in air. This results in a mixed microstructure that closely resembles the un-heat treated steel, or the normal structure of the steel.
- **Quench & Temper**: heat the steel to about 1700F, quickly cool (quench) and then re-heat to 900F to 1300F depending on the grade.
- **Stress Relieve**: Heat to 1100F and cool in air.
The term “Carbon Steel” simply means that carbon is the main alloy element, even though manganese is added to improve hot rolling characteristics. When manganese is added in sufficient quantities to make a contribution to strength or hardening, the steel is referred to as a “Carbon-Manganese” steel.

Alloy steels can be divided into several categories. HSLA is an abbreviation for “High Strength Low Alloy” and refers to a group of steels to which alloys like chromium, molybdenum, vanadium, columbium, etc. have been added to allow the steel to be heat treated to a strength level greater than that of plain carbon steels or carbon-manganese steels. Tool steels are very high alloy steels and typically contain up to 20% alloys. Stainless steels are a special group of steels that may contain up to 30% or more alloy.

Steel Grades

• Typical Grades use by smiths
  – Carbon steels (10XX)
  – Low alloy steels(15xx, 41xx, etc)
  – Tool Steels (O1, W2, D2, A7, H13 etc)
  – The last two digits give the average carbon content of the steel. The first two digits or the letter give the general alloy system (Manganese, Chrome-Moly etc.).
    • Note, this does not apply to tool steels or Stainless Steels.

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The Effects of Carbon

• Carbon is the most powerful strengthening element added to steel.
• The higher the carbon content, the harder and stronger the steel can be made.
• Most steel warehouses sell A36, 1018 and a variety of alloy steels. These are low to medium carbon steels.
• Tool Steels are often over .4% Carbon which can cause cracking during heat treatment.
The diagram above illustrates that over about .60% carbon in steel does not increase the hardness. However, tool steels often have more than 1% carbon because the carbon forms massive carbide structures. These are extremely hard and abrasion resistant and improve the steels performance. The open dots above are for alloy steels, the closed dots are for carbon steels. Note that the alloy content does not affect hardness.
Atomic Structure of Metals
All matter is made of atoms. In a gas, they are widely spaced and are totally without order. In a liquid, they are more closely spaced but still have no order. In a solid, they are very closely spaced and may or may not have any order. Glass, for example has no crystal structure and is called “amorphous”. Metals have crystal structures and are called “crystalline”. Different metals have different crystal shapes. Some metals, like iron can have many crystal shapes, depending on things like temperature and the presence of other metal crystals. The various crystal shapes have names like cubic, hexagonal, rhombohedral, etc. Only a few of the simpler, cubic shapes are important to this program.
Real Atoms

Electron Photograph of real atoms (Gold) as they appear in nature.
The “Body-Centered Cubic” crystal, called “Ferrite” has one atom at each corner and one in the center of the cube. This form of iron exists up to a temperature of 1340F.
Iron Crystal Shapes

Face-center Cubic: “Austenite”

The “Face-Center Cubic” is also a cube with an atom at each corner. It also has an atom on each face of the cube. This shape is called “Austenite” and usually exists only above 1340F.
The “Body-Center Tetragonal” crystal is called “Martensite” and is formed when the “Face-Center Cubic” Austenite is rapidly cooled. It is just like the “Body-Center Cubic” except it is stretched in one direction.
As we have already learned, steel is a mixture (alloy) of iron and other elements. The most important element is carbon. Carbon controls the strength and hardness of steel. The carbon is dissolved in steel like sugar in tea. However, not all of the carbon will dissolve into the austenite when the austenite is formed. Some of the carbon is tied up as iron carbides. To achieve the full hardness in quenching, the iron carbides must be given time at temperature to dissolve. Depending on the alloy and the carbon content, time at temperature can range from a few minutes to one hour per inch of thickness.
Ferrite will not dissolve very much carbon because the atoms in the crystal are too close together. Austenite, with larger atomic spacing, will dissolve much more carbon. However, it takes time for the carbides to dissolve and for the carbon to spread out from the carbide to dissolve in the austenite. Holding the steel at temperature will improve the as-quenched hardness.
Iron Carbides

Carbon (Yellow) will bond with 3 iron atoms (Gray) to form iron carbide (Fe₃C). This is a very stable carbide and requires time at temperature to break it up.

Carbon will also form carbides with chromium, vanadium, and many other alloy elements. Most carbides are very stable and must be soaked at the austenitizing temperature to dissolve them back into the austenite.
Like the sugar in tea, not all of the carbon stays dissolved. It forms iron carbides which create interesting new microstructures. Sometimes, the iron carbides form as long fingers in the ferrite. When this happens, the structure is called “Pearlite” because of its pearly iridescence.
Pearlite forms when the steel is heated to about 1650°F and allowed to cool in air. If it cools very slowly, the fingers will be widely spaced. If it cools more rapidly, the fingers will be closely spaced. If the steel is cooled very rapidly with water, the fingers do not form. Instead, the austenite transforms to martensite. Here, the carbides form as tiny spheres rather than fingers. The iron in martensite is not the cubic form called ferrite. Rather it is a distorted cube, the body-center tetragonal shape. The carbon forms very fine iron carbides dispersed throughout the martensite. Carbon contributes to the hardness of martensite by exaggerating the amount of distortion of the tetragonal crystal.
Phase Diagrams and Cooling Curves
Introduction

• In this section, we will use the following topics to illustrate the behavior of steel:
  – Phase diagrams
  – Isothermal Transformation Diagrams
  – Continuous Cooling Curves
  – Hardness VS Hardenability

Don’t let the big words scare you. We only want to understand what happens to steel when it is heated and cooled and these diagrams help us do that. They are useful to illustrated the behavior of the steel when it is heat treated. It is not expected or useful to learn how to use these diagrams, only that you understand in general what is happening. This will help you understand the heat treating process better.
Iron will exist in different crystal shape at different temperatures. The iron carbides will exist in different shapes depending on the amount of carbon and how it is cooled. Metallurgists have created a “map” of what iron crystal shapes (called “phases”) exist at different temperatures and carbon contents. These maps are called Phase Diagrams.

To understand how to use a phase diagram, we will create part of one here.
First, we draw a graph like the one shown above. On the vertical axis we will plot temperature and on the horizontal axis we will plot the amount of carbon in the steel. For this project, we have selected 9 samples of steel. Sample 1 has almost no carbon. Sample 2 has .2% carbon, Sample 3 has .3% carbon and so forth. We look at the microstructure of the steel in Sample 2 at room temperature and observe that is is made up of ferrite and pearlite. At the intersection of 70F and .2, we write “F&P”. Now we heat it up to 700F and look at the microstructure. It is still ferrite and pearlite so we mark another “F&P as shown. We continue to heat the sample to 1400F and discover that the pearlite has almost disappeared and a new phase is developing. The new phase is austenite (Face-center Cubic iron). The carbon has dissolved into the austenite leaving only ferrite and austenite. We mark “A&F” at the intersection of 1400F and .2%. We now heat the sample up to 1600F and see that now the ferrite has disappeared and only austenite is present. We mark an “A” at the intersection of 1600F and .2%. We see only austenite at 1800F and mark the graph with another “A”.
We continue to make our observations on the other samples and record the results. The top chart above is a summary of our tests. If we then plot all of the result on the original graph, we have something that looks like the bottom chart.
If we then draw lines to connect similar observations, we begin to draw part of the phase diagram for the Iron-Carbon system.
This is a copy of a real phase diagram for the Iron-Carbon alloy system. The area outlined is the portion we plotted. Note that there is a large portion of the diagram we did not evaluate. That is because those areas are for temperatures and carbon contents not used in normal smithing products.
What this tells us

• For different carbon contents and temperatures, the steel will have different phases, or crystal shapes.
• Knowing what temperature corresponds to austenite for a given carbon content will assure good heat treatment.
• Remember that it takes **time at temperature** to form austenite and to dissolve carbides.
Non-magnetic Point

Note that the line that indicates the non-magnetic temperature follows the A3 line down to the A1 line at the eutectoid point! That means that for steels with carbon contents greater than .8%, heating just to non-magnetic does not achieve the austenitic state needed to quench to martensite! It must be heated above the Acm line to be fully austenitic.
The word “isothermal” means at one temperature. These curves were created by allowing the metal to transform at one temperature. This is not what occurs when we quench where the steel is continuously cooling but it illustrates what happens.

Like phase diagrams, Isothermal transformation diagrams are created by heating steel samples of a specific chemistry to a temperature where they are entirely austenitic. The samples are usually very thin strips of metal. After the strips are heated, they are plunged into a crucible containing molten salt. The molten salt is heated to a specific temperature of interest. The strip will rapidly cool to the temperature of the salt and it is held at that temperature for a specific time. During that time the microstructure is monitored. The time for austenite to start transforming is recorded. When the transformation is complete, the time is recorded. The microstructure of the strip is then evaluated as is done for phase diagrams. Once again, we can construct a simple curve to understand what it is good for.
To begin our experiment, we construct a graph like the one shown above. Remember that the temperature at which iron begins to transform from ferrite to austenite is 1333F. It is also the temperature at which austenite will begin to transform back to ferrite upon cooling.

We heat our strip sample to 1550F, plunge it into molten salt at 1300F. We hold it in the salt. The microstructure is observed while the sample is held at 1300F. After about 30 seconds the austenite begins to transform to ferrite and pearlite. At the end of 60 seconds the transformation is complete. The two points are plotted on the diagram. We continue to do this for 4 more temperatures, 1200F, 1000F, 800F and 600F. When we rapidly cool the strips down to below 600F, we discover that instead of transforming to ferrite and pearlite, some of the austenite transforms to martensite. However, no matter how long we hold it below 600, no more or the austenite will transform to martensite. To form more martensite, we find that we must continue to lower the temperature. When we rapidly cool the sample to room temperature, we find that all of the austenite has changed to martensite. By connecting the dots, we have a map of transformation microstructures.

We have also established that for this particular chemistry, the transformation from austenite to martensite begins at 600F and ends at room temperature. Now, what good is this diagram?
The above page is taken from the ASM book “Atlas of Isothermal Transformation and Cooling Transformation Diagrams.” It shows the start and stop lines for 5160 at various temperatures. It must be remembered that this is for ISOTHERMAL transformations only. It is not entirely accurate when you are actually cooling the part by quenching. However, it does give some general ideas as to what is possible. Note the red line from 1400 to about 450F. This is the minimum quenching speed needed to get to the martensite start temperature without getting any ferrite or pearlite. The chart suggests that the part must be cooled from 1400F to 450F in about 45 seconds.
Let us assume that we can cool a piece of this steel to room temperature from the austenitizing temperature following curve #1. Where curve #1 intersects the first cooling curve (30 seconds), the austenite will begin to transform to ferrite and pearlite. When it intersects the second cooling curve (45 seconds), the transformation will be complete. The microstructure of this sample will be entirely ferrite and pearlite.

Now let's cool a sample of the same chemistry using the cooling rate shown in curve #2. Again when the curve intersects the first cooling curve (25 Seconds) the austenite begins to transform to ferrite and pearlite. However, before it can reach the second cooling curve, it reaches the martensite start temperature of 600F (Ms). At this point, the austenite that has not already transformed to ferrite and pearlite will begin to transform to martensite. Upon cooling to room temperature, we find the microstructure to be about 50% ferrite/pearlite and about 50% martensite.

We now cool a sample using curve #3. Since it never intersects the first cooling curve (called the pearlite nose), none of the austenite will transform to ferrite and pearlite. It will all become martensite if we continue to cool it to room temperature.

Cooling curves like this one, although much more complete, exist for almost all standard steel chemistries. It is a very useful tool to determine how much time you have to quench a piece of steel to achieve 100% martensite, or predict the microstructure if you do not have enough time.

Another set of curves, call Continuous Transformation curves plot the hardness and microstructures for a variety of cooling rates for common alloy steels but they can be confusing and will not be dealt with here.
This is an actual Continuous Cooling Curve for 5160. It is one of the simpler ones. This chart is a guide to what microstructures you can expect with various cooling rates. Cooling rates here are based upon a nearly perfect quench so that the rate limiting factor is the speed at which heat can conduct through the steel. This means the cooling rate is a function of the thickness of the steel. Each curve is for a different thickness (actually, diameter) of steel. At the left side, the 1/16” thick steel can be quenched to 100% martensite. The next curve is 1/8” and this cooling rate crosses the ferrite start line about 1000F. Between 1000F and 550F (the Ms line) it will be forming ferrite. What ever is left of the austenite will form martensite below 550F. The 3/16” line crosses the ferrite start line at about 1050F and the ferrite begins to form. However, at about 1000F, it hits a Bainite start line (bainite is sort of a cross between ferrite and martensite) and the bainite forms down to the Ms temperature. Below the Ms temperature, the remaining austenite forms to martensite. You can read the remaining reactions. The point of this is that a single steel alloy can produce a wide variety of microstructures, hardnasses and strengths by changing the cooling rate during heat treatment.
What That Means

• The speed at which a steel cools will determine the microstructure.
  – Slow cooling = ferrite and pearlite
  – Fast cooling = martensite

• The thickness of the metal will control how fast it cools. Heat will flow out of the steel only as fast as it is conducted through the steel.

• Thick parts cool fastest on the surface and slowest in the center. This will result in a mixed structure unless the right alloy is chosen to provide appropriate hardenability.
Hardness VS Hardenability

• Hardness is usually measured using a diamond point pressed into the surface of the steel. The softer the steel, the deeper into the steel the point goes and the lower the indicated hardness.
• Hardenability relates the how deep into the steel a specific hardness is developed.

Hardness is a measure of steels ability to withstand distortion, abrasion, or penetration, depending on the type of hardness test. Hardenability is a measure of the depth to which, by chemistry and quench speed, a steel can be transformed to martensite.
The Jominy Test

A Jominy bar is machined from a sample of the steel to be tested. It is then heated to the correct austenitizing temperature. Next it is quenched with a stream of water flowing against the end of the bar only.

We learned in our discussion of cooling curves that the rate at which steel is cooled determines the resulting microstructure. We also learned that ferrite is usually very soft, that a mixture of ferrite and pearlite is a bit harder, that all pearlite is harder still and martensite is the hardest. The Jominy test can provide actual hardness data on a specific chemistry. By measuring the hardness at 1/16th inch intervals, the depth to which a specific hardness is achieved can be determined.
When we quench only the bottom of the bar, the cooling rate at the bottom will be greater than the cooling rate, say, one inch up the bar. That is because the heat one inch up the bar must flow down that one inch to the point where the water is removing the heat. The different cooling rates up the bar will cause different microstructures to form. Each microstructure will have a slightly different hardness and the hardness can be measured.
Cooling Curves and Jominy Tests

After the bar is quenched cold, hardness tests are run down the bar in 1/16th inch intervals. J1 refers to first 1/16th position, J2 refers to the second 1/16th position, etc.

Hardness tests are run every 1/16th of an inch up the bar and recorded. The hardness is measured in Rockwell C units.
Above is the hardness data taken from the Jominy Bar. The values are in Rockwell C units.
The graph above is a typical Jominy hardness curve, plotted from the data on the previous slide. It tells us that for the distance between J0 and J1, the hardnesses are so similar that the microstructures are probably also very similar. Note that it begins to drop off after J1 and continues to drop to J5. The microstructures of points J2 through J5 are probably mixtures of ferrite and pearlite. The microstructure of J0 and J1 are probably martensite. Since J0 and J1 are hardened to martensite, the Jominy Hardness for this steel is Rc44 at J1. Beyond J1, there is not sufficient martensite to consider the structure to be hardened.

The chart tells us that this particular chemistry can be fully hardened to a depth of about 1/16th of an inch. If we were asked to quench and temper pipe made from this chemistry, we could not expect to harden a wall thicker than 1/16th of an inch. By using Jominy tests, metallurgists can determine the correct chemistry for each wall thickness that must be quenched and tempered.
The Jominy test is a standardized method used to compare various alloys under one cooling condition. It does not necessarily represent the fastest cooling rate possible and may not indicate the highest hardness achievable. However, it is a convenient way to illustrate how hardness varies with the alloy content and with the depth into the steel part.
What Controls Hardness?

- Carbon content controls hardness up to about .65% carbon. More carbon than .65% does not appreciably increase the hardness.
- The speed at which a steel is quenched also controls hardness for any given carbon content.
- Heavier sections will probably not harden all the way through.

The carbon content in the steel controls the hardness of the steel after quenching. However, remember the lessons on microstructure. Carbon can be dissolved into the austenite crystals and it can exist as iron carbides. Only the carbon dissolved in the austenite can contribute to the hardness. That is why steel must “soak” at temperature to dissolve the carbides and put the carbon back into solution in the austenite crystals.
What Controls Hardenability?

• Carbon content contributes most of the hardenability in a plain carbon steel.

• Alloy elements such as chromium, vanadium, molybdenum, boron, etc are also added to promote deep hardening in alloy steels but do not significantly affect hardness.

Hardenability refers to how deep into the steel martensite can be formed, not how hard it will get. High carbon steel will get very hard (Rc60+) but this hardness may only go in .050". On the other hand, D2 tool steel will get to Rc60 and this hardness may develop to a depth of 4-5"!
The blue line (#1) shows a steel, like a D2 tool steel, that is hard on the surface and is hardened deeply.

The gold line (#2) shows a steel with enough carbon to harden the surface to the same hardness as the blue line but the hardness drops off quickly because it has no alloy (like a 1085).

The red line (#3) shows a low surface hardness (low carbon content) but the hardness is developed deeply. This is a low carbon, high alloy steel like 8620.

The pink line (#4) shows a low surface hardness and no depth of hardening. This is a low carbon, non-alloy steel like 1018.
Review

• Carbon content controls hardness; more carbon, more hardness.
• High carbon content can cause quench cracks if the steel cools to fast. This is because more carbon is trapped in the austenite crystals and they distort more when they transform to the martensite crystals. This puts more strain on the crystal lattice and may cause cracks.
• Even high carbon steel will not harden if cooled too slow.
• Hardness on the surface may be very different from the hardness at the center of the part.
• Martensite begins to form at about 600F. If you get the part to the Ms temperature before the pearlite begins to form, it can be slowly cooled to room temperature.
Heat Treating Processes
Recall the phase diagram we made earlier. Above is a copy of the lower left corner which is where we do most of our work in heat treating. Note that there is one point called the eutectoid (you-tek-toid) where steel will transform directly from ferrite & pearlite to austenite. This occurs at .78% carbon (red dashed line). For all other carbon contents, the steel does not transform to austenite immediately, it gradually transforms over a range of temperatures between the A1 and A3 lines. Between these two lines, iron will exist as a mixture of ferrite and austenite. It is called a two phased region.

Martensite will only form from austenite. If you do not heat it sufficiently to completely transform the ferrite & pearlite to austenite, you will not get as much martensite in the quench. Hardness will be lower, too. Heating to just non-magnetic may not be quite hot enough.
Quench and Tempering

- Quenching
  - Low carbon steels need a very fast quench medium, like water or brine to cool quickly enough to form martensite.
  - Medium carbon steels may be water quenched.
  - High carbon steels are usually oil quenched.
  - Air hardening steels are not quenched but left to cool in still air.
- Quenching Medium
  - SuperQuench is reputed to be the fastest liquid quench medium. However, the speed at which heat conducts through the steel is what controls the transformation.
  - Cold Brine is very fast and good enough for most low to medium carbon steels.
  - Plain water, well agitated is good for medium carbon steels.
  - Oil is used for high carbon steels.
  - Air is considered the slowest “quench” and may be the correct medium for some air hardening tool steels.

This process should actually be called “austenitizing, quenching and tempering”. However, everyone knows what we mean when we just say “Q&T”. The temperature used for austenitizing is determined by the chemistry. When the steel has been quenched, it becomes very hard and brittle. To lower the hardness and restore some ductility, it is tempered (sometimes called “drawn”) at a lower temperature. The higher the temperature for a given time, the softer the steel will become. Conversely, if the time available is long, we may adjust the temperature down and get the same hardness as we got using a shorter time and a higher temperature.
Agitation

- In order to remove heat from the steel, the quench medium must contact the steel.
- If steam is forming in water quenches, it will insulate the steel and quenching slows down.
- Any liquid quench should be agitated strongly or the part moved in a figure 8 in the quench to keep heat transfer even.

Heat is transferred most efficiently when there is a large temperature difference between the heated object and the quench medium. As the quenchant is allowed to contact the hot object, it gains heat and its temperature goes up. As its temperature goes up, heat transfer rate goes down. To get the most out of a quenchant, it must be agitated so that fresh quenchant is always contacting the hot object. Agitation also moves the hot liquid to the surface of the container, allowing some of the heat to radiate into the air.

Agitation of oil will also help prevent overheating of the oil in contact with the hot part and minimize the potential for a fire. Warming oil to about 125F-150F improves the quench rate by making the oil more fluid and easier to agitate.
What is happening in tempering? As-quenched steel is in a highly distorted crystal shape (body centered tetragonal) with carbon trapped in the voids between the atoms. By heating the steel, the carbon atoms can escape from the martensite crystal and form carbides. This is similar to letting air out of a tire. Hotter or longer tempering “lets more air out of the tire”. The carbides get bigger and the crystal shape slowly goes back to body centered cubic: Ferrite. If tempered long enough, the steel is just ferrite and carbides.

Different chemistries will achieve different hardness when tempered at the same temperature. The addition of alloy elements like chromium and molybdenum will keep the steel from softening as much during tempering while allowing it to achieve superior toughness. Note that the steel cannot be tempered hotter than about 1300F or austenite will begin to form, ruining the heat treatment. Steel can be water quenched AFTER tempering without affecting the hardness but it may cause the part to bend due to thermal shock.
The above photomicrograph shows what tempered martensite looks like at 100x magnification.
Metallurgical Effects of Tempering

- Tempering starts at about 250°F where very small iron carbides begin to precipitate in the martensite.
- As the temperature is increased, precipitation rate increases and carbide size increases.
- Hardness drops as temperature (or time) increases.
- Continued tempering will return the steel to a fully ferritic structure with large carbides.
  - Toughness is the measure of a steel to the propagation of a crack. If a crack is already in the part, it can propagate during quenching or tempering (due to thermal shock and expansion of the part).
Tempering Methods

- Some smiths employ a “snap draw”. This is just heating to a target temperature and letting the part cool in air. This is usually done by oxidation color.
- The snap draw will work on thin pieces but does not ensure the insides of a heavy section have reached the desired temperature.
- Furnace tempering is better and more accurately controlled.
- Soaking at the target temperature for 1 hour per inch of thickness is normal procedure.
Temper Colors

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<th>Fahrenheit</th>
<th>Color</th>
<th>Celsius</th>
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<td>216°</td>
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<td>221°</td>
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<td>Brown with purple spots 1, 2</td>
<td>520°</td>
<td>271°</td>
<td>Steel grey 2</td>
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Chart courtesy of Anvilfire.
Distortion and Quench Cracks

- Can be caused by:
  - High austenitizing temperatures (thermal shock)
  - High Carbon Content (high lattice strain)
  - Non-uniform heating or cooling (differential expansion and contraction)
  - Surface defects (stress risers)
  - Inclusions (stress risers)
  - Sharp Corners (stress riser)
  - Large changes in section thickness (differential heating and expansion).

Quench cracks can be recognized by the fact that they usually are perpendicular to the steel surface. High carbon contents (over .40%) are very crack prone. Quenching from a high temperature can cause cracks as can un-even heating or cooling. Sometimes the crack starts at a surface defect or at an inclusion in the steel.

The temperature of the quench water can also cause cracks. Water should not be below about 60F nor hotter than 90F.

Heating oil to about 120F decreases the viscosity and improves contact with the part; this will actually make it quench faster. Remember, when using oil, always use about 5 gal per pound of steel and have a steel lid to suffocate any flames that flare up if the oil reaches the flash point.
Distortion and Quench Cracks

- The act of quenching is a balance between thermal expansion (when the part is heated), thermal contraction (when the part is quenched), and the expansion involved in the transformation of austenite to martensite.
- Austenite will expand from .4% to 1.2% as it transforms to martensite.
- Depending on the residual stresses, all of the above can cause quench cracks or distortion of the part.
- Since the OD of the part transforms first, it expands and becomes brittle martensite first. Then the steel under the skin of martensite begins to transform and expand. It is trying to expand against hard, brittle martensite and may cause cracking.
Normalizing

- For most products, the steel is heated to 1650F-1750F and allowed to cool in air.
- The microstructure is ferrite and pearlite.
- It is performed to make the microstructure more uniform, and disperse the carbon evenly throughout the part.
- It will also reduce the grain size if grain growth occurred during forging.
- It should be done once or twice prior to quench and tempering.

Normalizing is similar to quench and tempering in that it often heats the steel to the same temperature. However, the steel is not quenched but allowed to air cool. Instead of forming martensite, it forms ferrite and pearlite. This process does many things. It “erasers” the changes in the metal due to welding and forging, it relieves forming stresses, and makes it easier to machine.

Normalizing several times at succeeding lower temperatures can reduce grain size. As in austenitizing, normalizing benefits when the part is held at temperature for a period of time. This allows the carbides to dissolve and diffuse, creating a more uniform distribution of carbon in the steel.
Annealing

- For most products, the steel is heated to about 1550F and SLOW cooled, sometimes it is cooled in the furnace.
- Microstructure will be mostly ferrite with large iron carbides.
  - Note that this is NOT a good microstructure from which to harden steel.
- Material will be at its softest.

Annealing can take place at a wide variety of temperatures. At low temperatures (900-1000F), it is sometimes called “stress relief annealing”. No changes to the steel microstructure occur but the stresses in the pipe are relaxed. At temperatures in the 1000F to 1300F the steel microstructure begins to change and get softer. At temperatures over 1350F, austenite can re-form and iron carbides can grow. For annealing to have maximum effect, the steel must be slow cooled. Sometimes this means leaving the steel in the furnace and lowering the temperature by 50 degrees per hour.
Stress Relief Annealing

- Stress relief annealing is usually done at 900F to about 1200F.
- It relieves stresses from cold forming and straightening. This will help maintain tight tolerances if the product is machined.
- There is very little change in the microstructure at these low temperatures.
- Note that stress relieving cannot relieve ALL of the stresses in a part. Only in a liquid state does a material have no internal stress. It must have some internal stress to resist externally applied stress.
- There is a practical limit to stress relieving times; usually one hour per inch of thickness is sufficient.
The End