Metallurgy Lesson 1. By Terry Pehrson, username 38Chevy454, metallurgical engineer, gearhead, hot rodder, Made in USA bear claw latches sales, landspeed addict, and very slow landspeed race car builder.
****

Let's start with a focus on the basics of what metal is. We'll get into more detailed topics later. I'm going to focus primarily on steels, as that is what 90% or more of what we deal with on hot rods and race cars is made from, but most of the the discussion applies to all metals. So grab your favorite beverage and let's see what we can learn.

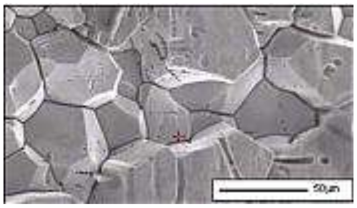
Microstructure

As liquid metal cools, many small crystals begin to form. As the metal cools further, the crystals grow, until it eventually forms a solid composed entirely of many small, tightly packed crystals (also called grains). The solid has less volume than the liquid, so you get some shrinkage during solidification. This is opposite of water where solid water (ice) has larger volume than liquid. In metals the shrinkage from liquid to solid contributes to distortion in welding and also to porosity in castings. Now back to our discussion on the packed crystals. Within each crystal or grain, the atoms are arranged in a very specific pattern, called the crystal structure. You have all heard the expression "It crystallized and broke", well that is total BS. Metals are ***always*** crystal structure when solid. The crystal structure configuration may change, and that has significant effect on the properties, but it always has a crystal structure.

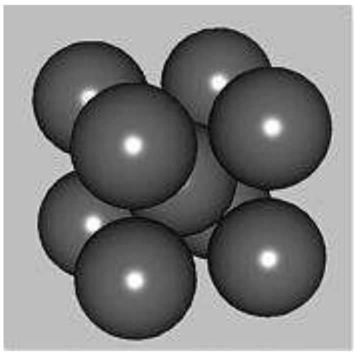
To picture the arrangement of atoms in a crystal, imagine a stack of cannonballs, where each cannonball represents one atom of a material. There are different patterns that the cannonballs (atoms) can be arranged in. For example, when starting a new row in the stack, you can place the cannonballs in the divots between each ball in the row below, or you can stack them directly on top of the balls in the row below (ignore that in real life if you tried this they would not want to stay that way without some constraint holding them in position). In a metal, the specific pattern that the atoms arrange into depends on the type of atoms (for example: iron, aluminum, or titanium), and the arrangement of those atoms determines many of the properties of the metal.

When a metal is flexed or stressed enough to cause deformation, some of the atoms inside each grain slip past each other. In some crystal structures this slip can occur more easily, which results in a less strong and more ductile metal, and in other crystal structures the slip is more difficult, resulting in a higher strength material. The boundaries between each grain help resist the deformation, thus smaller sized grains will result in higher strength. Normally the grains are very small; a typical grain size for steels would be approximately 0.002" across. Grains are not shaped as exact cubes or round balls, they are irregular shape. The crystal structure alignment within a grain is all the same orientation, but neighboring grains will have different orientations, which also contributes to making the metal stronger. A good visual example to imagine the grains and the crystal structure is rock candy, which has the various grains and the different crystal orientations easy to see.

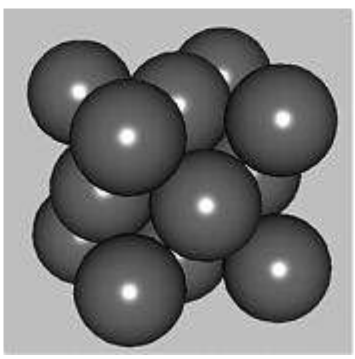
When you heat or cool a metal, you can cause the atoms to rearrange. This is called a phase change, and dramatically changes the properties of the metal. Most steel that we deal with is not heat treated and is in a phase called ferrite. In this phase, the arrangement of the atoms is Body Centered Cubic (BCC), which is a structure in which it is relatively difficult for the atoms to slip past each other, so the metal is fairly strong. If you heat steel to high enough of a temperature (approx 1400F), you begin to form a different phase called austenite. The arrangement of atoms in austenite allows them to slip much easier, resulting in a much softer and more ductile material. The specific arrangement of atoms in austenite, called the Face Centered Cubic (FCC) structure, is the same as that in other soft metals like aluminum, copper, gold and lead. The arrangement of the atoms in BCC and FCC structures are shown schematically in the attached images below. As a point of information, FCC structure in steel is non-magnetic, so red hot steel is not magnetic like it is at room temp, when it is BCC structure. Quenching steels from high temperatures can result in other phase changes, which will be discussed in the later topic on heat treating.



Typical grain structure of metals



Body Centered Cubic (BCC) Structure



Face Centered Cubic (FCC) Structure

Basic Chemistry

Steel used for automobile components is a mixture of iron plus up to about 1% carbon, plus small amounts of other alloying elements. Carbon is by far the most important alloying element in steel. Carbon is very efficient at increasing the strength of iron. The carbon atoms, which are smaller than iron atoms, fit into the spaces between iron atoms, helping to lock them in place and giving a higher strength material. Carbon can also combine with the iron or other elements such as chromium or vanadium to form extremely hard carbide (ceramic) particles within the steel, which increases hardness and wear resistance. Tooling is a common application for carbide steels. Too much carbon will create problems with welding. Pre-heat and post-heat requirements as well as controlled cooling rates can be required. Fortunately, most all of the pieces that we use for fabricating brackets and frames are low carbon and can be welded without any troubles (at least due to chemistry!)

Other alloying elements can be added to control specific properties of the metal such as strength, toughness, and corrosion resistance. Some elements are also added during the steel making process to control “tramp” elements (such as sulphur, phosphorus, and oxygen) that tend to reduce the toughness of the steel. Alloying elements can also affect the way in which steels respond to heat treatment, which will be discussed later. Some of the other most important alloying elements for steel are listed below, together with their effects:

Manganese: Helps to control sulfur, which causes brittleness in steels
Chromium: increases strength, forms hard carbides, increases corrosion resistance
Nickel: Increases toughness (resistance to fracture), increases corrosion resistance
Molybdenum: Increases strength, helps maintain strength at higher temperatures
Silicon: helps deoxidize the steel, oxides can cause lower strength and toughness
Vanadium: helps control grain size, helps maintain strength at higher temperatures
Titanium: helps to deoxidize, and also help control grain size
Aluminum: helps to deoxidize, and also help control grain size

We need to define some of the basic terms we will use so everyone has the same understanding of what the terms mean:

1. Yield Strength – the point where the metal will begin to permanently deform.
2. Ultimate Strength – the maximum stress the metal can take before it breaks. This occurs after a lot of plastic deformation which is a result of stress level beyond the yield strength.
3. Elastic Deformation – Stress level that is below the yield strength. The part will return to the original shape and size.
4. Plastic Deformation– this is permanent deformation of the part. The part will not return to the original size or shape.

Forms of Metal

Metals come in many different forms:

- sheet (generally defined as 0.187 inch thickness or less)
- plate (above 0.187 inch thickness)
- casting
- forging
- rolled shapes
- extruded shapes
- tubing
- drawn shapes

Each of these have applications that the design engineers choose to use based on the mechanical properties, appearance, manufacturing costs, material costs, availability or other factors.

Steel used on car parts is going to be made primarily of sheet, castings or forgings. Sheet metal is going to be used for body panels (duh….), frames, some brackets, suspension control arms and links; in fact most of the car would be considered sheetmetal. Castings are typically found in the engine, transmission and rearend cases. Forgings are also used in the engine and some internal transmission and rearend parts. Steel plate might be used for some brackets and link pieces.

Aluminum parts used on the car may include castings for engine parts, and transmission cases. Many cars have aluminum trim pieces made from sheet. There may also be some extruded aluminum shapes, especially on newer cars.

Older cast wheels (such as the torque thrusts) are usually cast aluminum. Some old magnesium wheels are cast magnesium. Later aluminum wheels can be forged or cast.

Follow along below and each form will be discussed in detail that will help you learn the advantages and disadvantages of each.

- Sheet steel – can be made into almost anything; using stamping, forming, and welding. Sheet is defined as less than 0.187 inch thickness most of the time. Sheet parts would not normally be heat treated as the distortion would make them unusable. Most all grades of sheet steel have the same ultimate tensile strength, but better formability grades have lower yield strength so they can form easier. The mechanical properties of the sheet have a direct effect on the formability of the sheet. There are several grades you may encounter when talking with your local steel supplier:

  - Drawing quality (DQ) – lowest ductility
  - Deep drawing quality (DDQ) – common and reasonably good forming.
  - Extra deep drawing quality (EDDQ) – not so common, this is good stuff if you can get it, able to form sharp bends without cracking.
  - Interstitial free (IF) – typically not found at local steel supplier, used by OEM's for real deep drawing applications. Has the most formability and is the best grade of sheet steel.

Sheet steel also is available in different surfaces and coatings:
i. Hot rolled pickled and oiled (HRPO) – this is a rougher surface and does not have good formability. Probably difficult to find at your local supply house in thin ranges, as the limit is about 0.080-0.100 inch thickness or more.
ii. Cold rolled (CR) – this is most common and may have a slight oiled surface to prevent rust. All grades are available in this and is what your local steel supplier will most likely have in stock.
iii. Electrogalvanized – this is cold rolled with electroplated zinc coating on the surface to give corrosion resistance. Zinc needs to be cleaned off the weld area before welding. New cars use this on outer body panels as the surface is very smooth and nice even coating. New cars use resistance spot welds and do not have the zinc removed prior to the weld.
iv. Galvannealed – this is zinc that is applied by hot dipping and then smoothing out. Has a darker grey appearance then electrogalvanized, but still for the same corrosion benefits. Typically used for non appearance parts such as floorpans or inner structure as the surface is a bit rougher.
v. Hot Dip Galvanized – this is mostly used for commercial applications and hardware, therefore not on cars.

- Plate – this is just thicker than sheet, greater than 0.187 inch thickness, but typically will be cold rolled. Usually does not have any zinc for corrosion protection. If you actually mess with thicker plate, buy cold rolled, the surface finish is much better. Hot rolled is available.
- Casting – a casting is just what everybody knows, molten metal poured into a mold. Castings have rougher surfaces that copy the mold surface, typically are low ductility and generally not used for high strength applications. A casting has a parting line where the mold pieces fit together; this is going to be around 1/16 to 1/8 inch size line. Cast steel or cast iron are usually not heat treated, aluminum is more common to see heat treatment done on a casting.
- Forging – used for high strength applications, such as spindles, crankshafts, gears and other areas where the metal is required to have high strength. Forgings are made by squeezing the hot metal between dies to force the metal to conform, which creates a desirable grain flow which benefits mechanical properties. Forgings can be made by fast squeezing between the dies known as drop forging, or slowly between rollers or dies. Forging is usually done at the high temps in the austenitic range for steel. See discussion on microstructure later in this lesson. Forgings have a parting line much thicker than castings, on the range of 1/4 to 3/8 inch thick. Most forgings will not be heat treated, but they could be, as their cross section is usually thick enough they will not experience major distortion during heat treating.
- Rolled shapes – this is what you see used in buildings for I-beams, C-channel, angle iron, etc. These are typically long straight sections and use lower grade steel that has lower ductility and lower mechanical properties than sheet or plate. It is satisfactory to use for some brackets, but not the best choice for frame pieces. Rolled shapes are produced by hot rolling a steel billet between successive rollers that form the shape. These are almost never heat treated and have the same rough surface like hot rolled sheet or plate since they are produced by rolling to shape at high temps.
- Extruded shapes – this is very common with aluminum bar and other shapes. This is produced by forcing the metal through a die, kind of like you see with kids and play-doh. Most aluminum shaped product (solid or hollow bars, angle, or tubing) is extruded to produce the shape. Aluminum sheet or plate is rolled.

- Tubing – for steel this is for round, square or rectangular. Most often is welded to enclose the shape. Produced by roll forming the sheet or plate into the desired enclosed tubing configuration, and then electric resistance welded together. Your common 2x3 box tubing that is a common frame material is made this way. Tubing can also be seamless. DOM, drawn over mandrel, is special tubing where a mandrel is pulled through the tube to keep the wall thickness is very consistent. Standard seamless tubing is not as consistent wall thickness, as it is made by drawing a hollow section through dies until final size and shape. There is really no reason to avoid welded tube unless you have a critical application where the weld can affect the mechanical properties.
- Drawn shapes – this is typical for wire or other small solid shapes. The metal is pulled through successively smaller dies until it is the final size, it is drawn through the dies. Because of the high amount of working to draw through multiple successive dies it has very high strength due to the cold working, unless it has a post-draw annealing to reduce the cold working induced stresses.

What does all this mean for the hot rod or race car builder? The answer is "it depends". This is because each application is dependent on the various factors that are a mix for the specific part. Obviously shape determines some forms of materials used. For the home builder that does not have access to all the specialized equipment, it may come down to what you can make work. Your fabrication tools, welding or joining techniques, and final appearance all affect this. Keep in mind that building something with stronger materials or overkill in design is better than skimping.

Steel Identification

The numbers that you see on steel or aluminum alloys are the designation that tells you the chemistry and in some cases the strength level. In steels you have typically a four digit number YYXX, such as 1018. 1018 translates roughly as: the first 10 means plain carbon, no alloying; the second 18 means nominally 0.18 percent carbon, actual specification range is approx 0.15-0.21 percent. There are numerous grades of "mild steel" of which 1018 is one grade. Mild steel is just a general term that really means low carbon and little or no alloying elements added. You may run across a designation such as A36 steel used. As in ASTM A36 is the specification the metal is built to meet, this is not a chemistry designation but more of a mechanical property designation. A36 is typical structural steel. Such as I-beams, channel, large plate, etc. Technically A36 is a mild steel, in that it is low carbon. The problem with A36 is that it is not as high of quality, varying chemistry and has more impurities and potential defects that are not desirable for parts that are cycled, such as suspension pieces.

Now back to the number designations, ask your steel supplier for "mild steel", that you want "cold rolled", not "hot rolled pickeled and oiled" (HRPO) and not A36, but something "***like*** 1010 or 1018". That will get you good material that you can weld without any troubles, as well as form to some degree without cracking.

Any "low alloy" steel, such as 4130, 4140, 4340, or other numerous grades are all small additions of alloying elements. You have heard of "chrome moly"? Well that means chrome and molybdenum are added to the steel, which is what the 41xx series are. The 43xx series are nickel, chrome and moly as alloying. You do not want these as they are going to create more welding problems. Unless you know what you are doing, stick with plain carbon types that start with "10" indicating plain carbon and no specific alloying elements added.

Stainless Steel

Stainless Steels (SS) have a whole new discussion. For a steel to be considered stainless it has to have at least 11% Chromium (Cr) added. SS are still mostly iron, they just have the extra Cr and other alloying elements. The Cr provides a thin chromium oxide protective layer on the surface of the steel. The term stainless is really a mislabeled name as the steels re actually corrosion resistant and not stainless; but the name has been around so long it is used even if not technically accurate. All stainless steels are considered weldable, although can have special techniques and limitations. You can join stainless to mild steel, use stainless filler metal for the weld. SS are typically given a 3 digit numbering system and can be divided into 5 types:

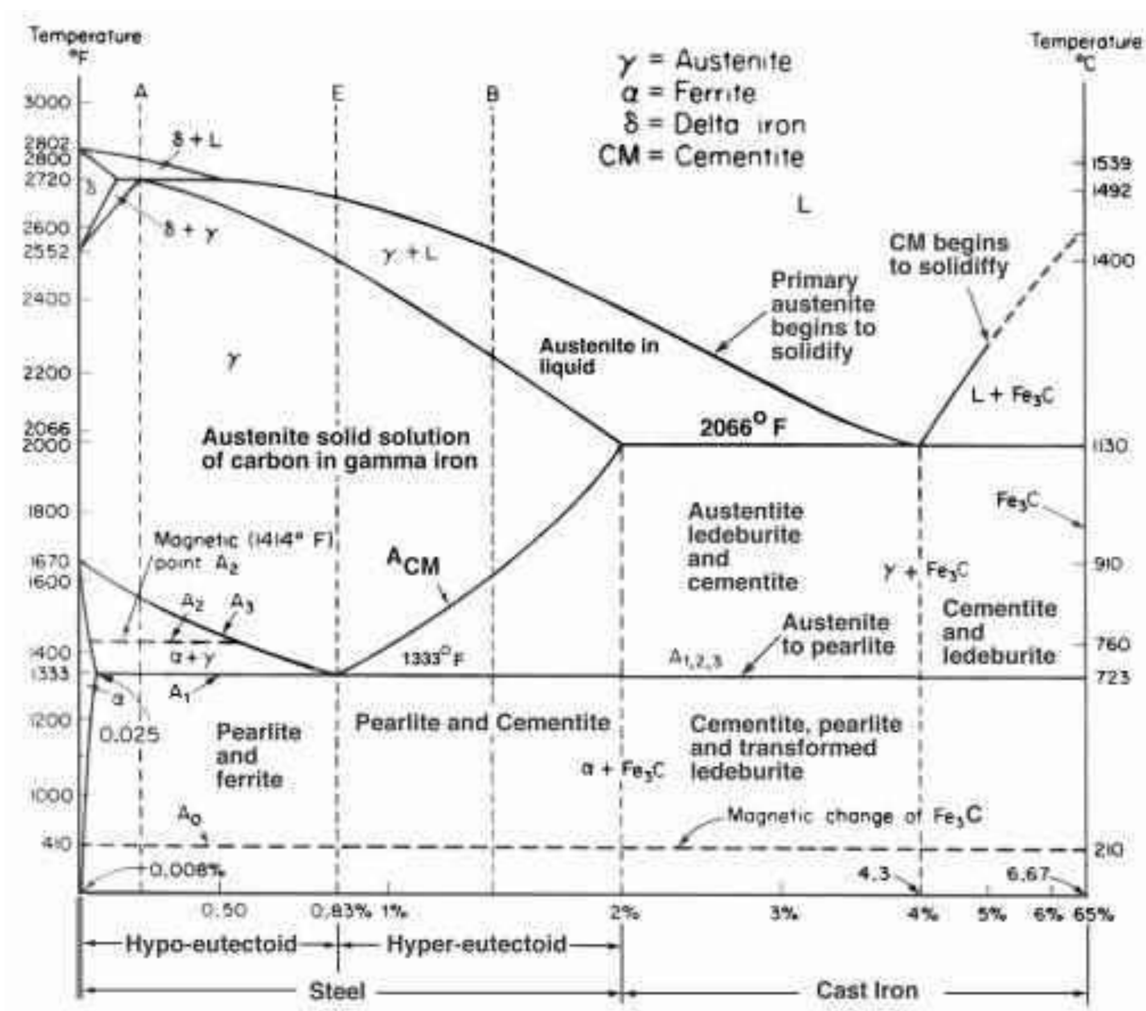
1. Ferritic – these have a ferritic BCC microstructure and are magnetic. Used where increased corrosion resistance is needed, but somewhat higher strength than the better corrosion resistance austenitic grades. Most common in thinner cross sections like sheet. Not heat treatable to make stronger as they have almost no carbon
2. Austenitic – these are the austenitic grades and are non-magnetic. 200 and 300 series are under this type. They are FCC structure and generally the best corrosion resistance. Typical numbers would be 201, 304, 316. Numbers may have an L on the end as in 304L which signifies low carbon. Not heat treatable to make stronger, as they stay in austenite phase and not able to transform to make martensite. The 300 series have additional nickel levels higher than the 200 series which provides better toughness and ductility.
3. Martensitic – these are the 400 series numbers and have the lowest amount of Cr. They are magnetic and are BCC structure. A lot of OEMs use 400 series stainless steels for exhaust components. Capable of being heat treated to make stronger. Least corrosion resistance of all the SS types.
4. Duplex – have a mixed microstructure of approx 50% austenite and 50% ferrite. This makes them moderately magnetic. Mostly used for the increased corrosion resistance and increased strength over the ferritic grades. Most difficult to weld since it has the mixed microstructure.
5. Precipitation Hardening – These are martensitic microstructure with additional precipitation hardening, so they reach the highest strength. Precipitates form which help lock up the ability of the atoms to slide over each other and therefore high strength potential. Magnetic like the Ferritic and Martensistic grades. Corrosion can be similar to the austenitic series. Typical example numbers are 17-4PH or 15-5PH. Since they require being heat treated to take advantage of the mechanical property potential they are also the most costly. Any welding will mess up the heat treatment. Parts are generally heat treated in the near final shape configuration so these will not be likely for your fabrication. You could run across PH SS fasteners that you would use as-purchased since they are in the final heat treated condition.

Sensitization is a specific subject that is good to discuss when welding SS. Sensitization is a phenomenon that happens in the HAZ of a welded SS whereby the carbon in the SS will get together with the Cr to form chromium carbides in the temp range of approx 600-1200F. What this does is make a locally chromium-depleted region that no longer has sufficient Cr to provide that protective chromium oxide layer on the surface. Mostly a problem for the 200 and 300 series grades where the increased corrosion resistance is desired. Look at some old welded stainless tanks and you will sometimes see a brown rust line next to the weld in the HAZ. Yes it is rust as in iron oxide, remember that SS is still mostly iron. To avoid sensitization, there are specific alloys that contain either Columbium (also called Niobium) or Titanium, types 321 or 347 respectively. Either Columbium or Titanium are stronger carbide formers than Chromium, so they tie up the carbon to prevent chromium carbides from being able to form in the HAZ or any area exposed to the 600-1200F range. By making grades of stainless with lower carbon, it helps the sensitization problem because there is less carbon potentially available to form the carbides to begin with. If you do have sensitization, the only way to make it go away is to heat the part above 1200F so the iron carbides dissolve and then cool fast through the 1200-600F range. Recall that the austentic grades are not heat treatable to make stronger so they can be water quenched.

Heat Treating

What is heat treating? Heat treating is a basic term that means using heat to alter the metal's properties. Heat treating can be used to make the metal stronger and harder, to lower the strength and make the metal more ductile, to increase corrosion resistance, or other reasons. Heat treating of car parts is typically done for higher strength and higher surface hardness. For iron-based metals (steel for example) there is a direct relationship between hardness and strength, as hardness goes up, so does strength. Not all metals have this direct relationship; aluminum is an example where increased strength does not follow directly with higher hardness.

In order to understand heat treating, you must first go into a little technical science here in this lesson. Carbon is the primary element that adds strength to steel when it is heat treated. All steels have some carbon, and the more carbon, the more potential strength you can get. Chemistry tells us that there are several forms that carbon can take in the iron. What we need to know to properly heat treat steel is at what temperatures do these different forms exist for a certain carbon content. The iron-carbon phase diagram gives us this information, and serves as the basis for all heat treating of steels.



Iron-Carbon Phase Diagram

The point of the iron –carbon phase diagram is that you have a solubility of carbon in the iron. In other words how much carbon can the iron hold at a given temperature. Without getting too involved, notice the line going across at 1333 F (723 C), labeled A1. That line is the austenitic transformation line. Now notice the line going up to left at approx 20 degree angle, labeled A3? All heat treating for strength requires the steel to be heated above this A3 line, so that complete transformation to austenite is made. Above this line all of the carbon in the steel is dissolved into the iron, and available to provide strength when the steel is quenched to room temperature. See the vertical line at 0.83% carbon? That is the eutectoid line, do not worry about the technicality of it, it is the carbon limit for steels where you start to get iron carbide. You really only need concern with the portion from 0.83% and to the left; above that point is for tool or bearing steel. Note that the technical definition for cast iron is greater than 2.0% carbon, and steel is less than 2.0% carbon content.

Quenching fast enough from high temperature above A3 forms martensite, which is the hard strong structure you want for high strength or hardness. In as-quenched martensite all of the carbon that you were able to dissolve into the austenite is still trapped in between the atoms, basically pre-stressing the steels crystal structure at a microscopic level. Because of this pre-stressing, as-quenched martensite is very strong, but also very brittle. Therefore after quenching martensite must be tempered (heated up to some point below the transformation temp and held for 2-4 hours typically) to bring down the hardness and bring up the ductility by drawing some of this carbon out to form small carbides. A file is very hard and strong, but brittle. Not a good choice for a spring where the part has to have some ductility. Nearly all heat treated steel parts are tempered martensite structure. If you heat a tempered martensite part up beyond the tempering temperature used on that part, it will lose strength as higher temperatures cause more carbon to be removed from the martensite.

Heat treating should not cause the part to shrink. Any shrinking is probably due to distortion. In reality and trying not to get too technical of terms, a part that is quenched to form martensite will actually be slightly bigger. This very small growth is why the cryogenic cold treating is popular for real precision parts. The reason is cold treating causes any retained austenite to transform, before the part is finish machined, so the part does not have dimensional stability issues once in service. Retained austenite is bad as it will cause a dimensional change if it transforms once a part is put into service. Stress or temperature cycles can cause retained austenite to transform to untempered martensite.

Why heat treat?

Heat treating is done most often to make the metal stronger and harder. Wear surfaces such as gears need high surface hardness. Bearings are also examples of hard surfaces. Springs are typically heat treated, whether leaf or coil. Any bolt of grade 8 or higher will be heat treated. Grade 5 is typically not heat treated, but stronger than a grade 2 due to the cold working process of forming the bolt head and roll formed threads. Heat treating provides the means to alter the material properties so that the part can serve the function for the life of the assembly or vehicle. It's true that most stainless bolts will be inferior to Grade 8's, there are options out there that will meet or exceed the properties of Grade 8. However, these options will be significantly more expensive. For an example, take a look at the fastener metallurgy discussion on the ARP website: http://arp-bolts.com/pages/technical_metallurgy.shtml. If you want to spend the money you can get something that will work, but the stainless bolts you buy at the hardware store will likely be inferior to Grade 5 and likely to have properties close to Grade 2.

However, heat treating can also be performed to make a metal more ductile so it can be formed easier. You all have heard of heating up steering arms to drop them? This is an example of heat treating in the simplest sense. A part that undergoes multiple forming operations may require an in-process anneal, to remove the work hardening and make the part more ductile again. Annealing is a heat treat operation that is used to make the metal soft. Annealing can also be used to remove residual stresses that have developed in the metal, such as those from welding. This is (obviously) referred to as a stress relief heat treatment, and is typically done at lower temperatures up to the A1 line. Whereas a full anneal which is above the A3 line. By keeping the temperature below A1, the actual structure of the metal is unchanged.

How to heat treat?

There are many ways to heat treat. The most common commercial practice is a furnace with some type of gas environment. The type of gas environment can affect the surface condition of the metal. Normal air will actually pull carbon out of the steel surface (decarburize), making the surface less hard, which in most cases is not desirable. An atmosphere with excess carbon can diffuse carbon into the steel, making a harder surface, which is common for gears or shafts that have wear surfaces. Putting carbon into the surface is called carburizing. For most alloy steel parts the atmosphere is controlled to match the carbon in the steel, so that no real change in surface carbon occurs. Heat treating can also be done in a high temperature liquid, typically a molten salt. A vacuum can also be used as the atmosphere (although technically vacuum means no atmosphere) with special sealed furnaces, resulting in a very nice surface finish on the heat treated parts.

Furnaces can be batch type, processing a load at a time. Think of your oven in your house, this is a batch type process. Furnaces can also be continuous, with a long belt that parts get loaded on one end and then through the high temp section, quench or cooling section and then out the other end. This is typical for high volume production.

Let’s talk about quenching. Once the steel part has transformed to austenite we quench it to form martensite. Quenching is typically done in a liquid: water, oil, or glycol. Water is fastest, glycol next and oil is slowest. Depending on the carbon content, too fast of quench can cause cracking. If you do not quench fast enough, you will not form martensite and the part will be low strength and too soft. The alloying content in the steel will strongly affect this range of proper cooling rates for heat treatment. Some highly alloyed steels will actually quench fast enough in air to form martensite, such as air-hardening tool steels for example. Most steels require a faster rate that is provided by a liquid to form martensite. You need to know the metal chemistry that you have to determine the proper temperatures and quenching procedures to get the desired end result.

Tempering is almost always done in an air atmosphere, as the temperatures are typically not high enough to cause any decarburization problems. Additionally air is free, any other atmosphere cost money. A typical tempering time is around four hours, but can vary widely from this time depending on the alloy and the desired result.

Who heat treats?

Commercial heat treaters exist in any industrial area. Many companies have in-house heat treating capability. Heat treating to form martensite on a part you fabricated is not something that can be typically done at home. You can anneal at home on small pieces, especially the stress relief heat treatment. Your self-cleaning oven gets to around 900F during the cleaning cycle and would do a pretty good job of stress relief anneal – just make sure you don’t get in trouble with your significant other!

How do I use this knowledge?

Since heat treating is not something you can realistically do at home, and us hot rodders like doing stuff ourselves, we need to understand what heat treating does for us and how to use it to our benefit. This means that if a part is heat treated we need to be careful to not mess up the heat treatment.

This means heating a spring up to lower your car is a bad thing to do. By heating red hot, you destroy the tempering and cause the martensite to be transformed to regular old non-heat treated ferrite and pearlite structure, the same form of steel as most of the steel the rest of your car is made from. Which means it is low strength and will not work as designed.

It also means that if you heat up your steering arms (not heat treated from factory) to drop them, do not quench them and potentially make them heat treated. You want steering arms to be ductile and bend, not break. Slow cooling is best, still air and no liquid. Another example would be to alter radius arms, such as later 37-up Ford with spring in front when you split the radius arms.

Another thing to avoid is welding on any part that has been heat treated for high strength. The heat from welding will mess up the tempered martensite structure and you have the same problem as the heated spring – a weak area surrounded by higher strength heat treated material..

The cryogenic deep freezing, usually using liquid nitrogen at -320 F, is just a method to ensure that you have complete transformation from austenite to martensite. Some steels are more susceptible to having a small amount (approx 1-2% or less) of austenite, even at room temp after quenching. So the deep freeze causes the retained austenite to become untempered marteniste. What can happen is the retained austenite can transform to untempered martensite due to stress or even from the heat energy of tempering. What you do not want is to have ***untempered*** martensite in a part, recall that is brittle. There is also a slight size differential between austenite and martensite, so there is a problem for real close tolerance parts as well.

There have been may heated debates in the fabrication world about heating steel to form it and what it does to the strength. Ron Covell (for one) shows the heat and form method of bending steel tubing in his videos. The heat just makes the metal easier to form, it is more ductile, this is not heat treating in the sense to alter the properties of the finished product.

It has always been stated that if you are looking for a soft (ductile) weld on steel, Oxy/Acetylene would be your first choice closely followed by TIG. MIG welds cool too fast and therefore cause the welds to become hard. But what about strength? MIG welds are strong, but not very ductile. However the base metal is still the weaker part for most welded pieces. The heat affected zone has the lowest mechanical properties. The weld itself is typically harder and stronger due to fast enough cooling rates with MIG that you get a mixed structure. What is the heat from Oxy/Acetylene and TIG welding doing to the surrounding metal in the HAZ? All welds have a HAZ, it is the area from the weld interface to where the heat flows out sideways from the weld. MIG welds actually have smaller HAZ.

Along these same lines, and I know that this has come up before but I feel that it should be included here, why do some say that it is OK to weld 4130 without post heat treating it and some say you do not have to post heat treat? 4130 has a relatively high alloy content and you can get untempered martensite in the HAZ, that is why MIG welds are not recommended for 4130 (aka chrome moly). So 4130 can be safely welded via TIG or Oxy/Acetylene without a post heat treatment? Short answer is that as long as you can prevent as-quenched martensite, with slow cooling, you can do it by whatever method will give those results.

What about Oxy/Acetylene welding of stainless steels in terms of what it does to the structure of the steel in the HAZ. In stainless steels you get what is called sensitization in the HAZ and it causes rusting in that small area. For example if you Oxy/Acetylene welded a piece of stainless. What are the mechanical properties of the metal in the HAZ after the weld is complete? The generally accepted practice by stress engineers when doing calculations is that the weld and HAZ have the lowest strength properties, similar to annealed materials properties. Mechanical properties (tensile strength, ductility, etc) are different than the effect on corrosion properties due to sensitization. Sensitized stainless is still just as strong, it just does not have the same corrosion resistance.

Another non-heat treating method to make metal stronger is by work hardening (WH). WH is done when bending the metal back and forth, or squeezing it to become thinner such as between rollers or dies. It requires plastic deformation of the metal; bending below the yield strength in the elastic deformation range will not cause any WH to occur. Cold working smashes the grains and makes for a lot more dislocations between the atoms and crystal structure which results in a metal where the atoms cannot slip past each other as easily, thereby increasing the stress level required to make it plastically deform. WH raises the yield strength of the metal.

I know that these questions are not exactly about heat treating, but they are about the effects that heat has on metal so I hope they help to increase understanding.

.

Welding

There are so many topics in regard to welding I will only touch the basics and you can ask specific questions. First define some terms:

1. Welding – melting into the base metals, can have filler metal added or not. You will have fusion of the base metals with the weld pool.
2. Brazing – no melting of the base metals. You get a metallurgical bond on the microscopic level, but no fusion between the base metals and filler metal. Brazing is usually temps higher than 1200F
3. Soldering – typically done at temps less than 1200F, same mechanism as brazing but at lower temps.

Filler metals are used to make a stronger weld in most cases. The filler can be many choices, it is best to have the filler metal as equal or better grade than the base metal. For an obvious example, if you weld stainless steel you want stainless steel filler, not mild steel filler. For brazing, it is many times a copper alloy, hence the origination of the term brazing being derived from brass which is a copper alloy. Silver or Phoshorous Bronze is also used as a brazing alloy. Phosphorous is typically added to brazing alloys as it provides a self-fluxing action. Most copper based brazing alloys melt in the 1600 F range, or about red hot on the steel. Most solders used to be a lead/tin alloy, although lead is being reduced and many solders you will find today are tin/xxxx alloys. Plumbing laws have outlawed lead containing solders for any water systems. Electrical solder can still have lead in it.

One key thing for any weld or braze joint is to make sure your joint fit-up was tight, and the contamination on the surface was near none, you should have a fine joint that will hold up and last. In brazing you do not melt the parent metal, the braze metal flows to fill in, kind of like glue. But much stronger as you do get some metallurgical bonding at the parent metal to braze metal interface. The key to a brazed joint strength is to have the fit between pieces real tight, like 0.001-0.003 inch. Properly done the joint will be as strong as the parent metal. Braze or solder alloys are low strength, so the strength is derived from the tight fit and the flow of the filler into the small areas. Flux is acidic, the acid has H+ (hydrogen) ions that attack any oxides on the surface of the metal. For best braze joint quality you need the clean base metal, not base metal oxide for the braze filler to bond to. Always clean off flux after brazing.

Welded joints need to have good penetration into the base metal for maximum strength. Proper fit up is critical so the weld pool is the right size. Earlier we mentioned that the weld cools fast and the weld pool is a mix of the filler metal and a small amount of base metal. Since the weld pool generally cools pretty fast, it is sort of like a small casting. The heat from the welding has to be above the melting point of the base metal to get proper fusion. The areas close by the weld are the heat affected zones (HAZ). The HAZ has temps that can be above the A3 line, or below the A1 line, on the iron carbon phase diagram discussed above. Because of this, the HAZ has a mix of potential properties and is typically why a good welded joint will fail in the region next to the weld itself, in the base metal. The HAZ mechanical properties are the lowest possible, so consider this in your designs. I understand welding is a requirement to join the metal, just be aware it causes many metallurgical grain structure level effects to happen. If you could heat treat an entire welded assembly, the effects in the HAZ could be reduced.

Gas welds (oxy acetylene) are very ductile because they cool so slow. That is why hammer welding is ideal with gas welding

Welding techniques are beyond the basic metallurgy, so we won’t discuss those here.

Corrosion Protection

Corrosion is the enemy of all metals. Most all metals are found in the earth as metal oxides, not as the metal itself. These oxides are reduced to become the pure metal. Since the oxide is the more stable form, nature wants to return your metal to that oxide form. There are several basic terms again that should be defined for understanding:

- Oxidation – the electrically driven process where a metal gives up a negative charged electron and produces a positive charged metal ion. This positive ion combines with a negative charged Oxygen ion and forms a metal oxide. In a separate reaction the negative electron usually combines with a positive hydrogen ion to make hydrogen gas.
- Electrolyte – any oxidation requires an electrolyte to carry the electron away. Most common electrolyte is water.
- Coating – can be metallic or non-metallic (such as paint). Most metallic coatings will be electroplated, but can be mechanical or dipped.
- Galvanic Corrosion – based on the galvanic series, it is a list of the corrosion potential of metals vs a standard reference for a given environment. Example: Magnesium has very high potential, Platinum is the least.
- Sacrificial Protection – the oxidation of one metal preferentially to another metal.
- Barrier Protection – using a barrier such as paint to keep the electrolyte from getting to the surface of the metal.
- Passivation – process that lowers the corrosion potential of the metal surface.

Avoiding Corrosion

The best way to avoid corrosion is to eliminate one of the required elements: Metal, electrolyte, susceptible surface. If you eliminate one of these there will not be any corrosion. Obviously you can't eliminate the metal, so you need to concentrate on the other two. The common electrolyte is water, it is all around us and hard to eliminate, so that leaves the best one to concentrate on is the susceptible surface. Either use a sacrificial coating like zinc plating on steel, or use some form of barrier to keep the electrolyte away. Paint is the most common barrier, but there are also metallic barriers. Chrome plating is a barrier for steel. The typical chrome plated part has copper, then nickel and then final chrome layer. Copper is used to smooth the surface, nickel is the main corrosion resistant barrier, and the chrome is for appearance. These layers keep the water from getting to the steel surface. If we go back to the galvanic series, iron (the steel is iron remember?) is higher potential than copper, nickel or chrome. Ever see a chrome plated bumper where the chrome foil layer is bubbling up and the rusted steel underneath? That is because the steel is actually sacrificing itself to protect the chrome layers! As long as the chrome layers are intact, they provide a barrier. But if the layer is disrupted, the water electrolyte can get to the steel and thanks to galvanic coupling the corrosion rate of the steel is increased.

If you have done plumbing, you might be familiar with a part called a galvanic coupling. The function of these is to break the electrical conduction path between dissimilar metals. You avoid the galvanic coupling of the two different metals and therefore do not accelerate the corrosion of one part to protect the other.

A coating can also be oil or grease. On old cars that used to have draft tube to get rid of the crankcase vapors it was a side benefit that the oil vapors would condense on the cooler metal of the chassis and would give an oil based barrier to prevent the water from getting to the steel surface. This is the exact same mechanism as paint has.

New cars use a lot of zinc coated steels. The zinc has high potential vs iron and it will oxidize preferentially to the iron. Since the zinc is relatively thin, it will be used up and you will get iron oxide (aka rust) eventually. Zinc is what you find on all hardware you buy at the store. The color of zinc is silver and then a chromate conversion coating is put on top. This chromate can be clear (actually very slight blue tint), yellow to gold, olive drab or even black. In the old days people would call parts as being "gold cad" meaning they were cadmium plated with gold chromate. Cadmium is not used much anymore due to being carcinogenic; zinc has pretty much replaced all applications that used to be cadmium.

Salt increases the conductivity of the electrolyte. It does not change the basic corrosion mechanism. The salt just allows the oxidation of the iron to continue at increased rates as it allows the electron to go away easier, thus the reaction continues.

Passivation is just making the surface a lower potential and therefore has less electrical difference to drive that oxidation process. Higher electropotential wants to give up more electrons. Passivation does not affect strength, just the corrosion potential.

Electroplating

The most common way to put a metallic coating on the metal is by electroplating it on. One hazard of electroplating is that hydrogen is formed at the metal surface. Almost all plating baths are acid-based, so by definition they have excess hydrogen ions. The electrons are provided by the electroplating process, and while the desired result is that the positive charged metal ions in the bath become metal on the surface, some electrons make hydrogen. Why is this critical? Because the hydrogen can diffuse into the metal and cause hydrogen embrittlement (HE). HE is bad as it causes parts to fail. The exact mechanism for HE failure is an intergranular crack. For HE to happen you must have a susceptible metal, and a sustained tensile stress level above the threshold. The typical threshold is about 50% of yield strength. Susceptible metals are those that can have HE cracking, and are generally for our purposes are going to be heat treated steel parts. The general cutoff is about Rockwell C scale of 30 or higher to be considered as susceptible. Springs are a perfect example of this. Most suspension parts are not heat treated, but springs are. A weld can have high enough hardness to be considered susceptible. To reduce the potential cracking of a susceptible part that is plated, a hydrogen embrittlement relief bake is specified. This is usually around 400F for four hours and best to be as soon as possible after removal from the plating bath. It does not make it completely HE proof, but it does have good effectiveness. An HE crack is intergranular as stated previously and will have a rock candy appearance. A true HE failure will usually occur within 72 hours after the part is loaded up with some tensile stress. What many people say is a HE failure is not. If the fracture surface is not intergranular it is not HE. Most failures on cars are fatigue cracks which are cyclic stress loading and take a long time to initiate and propagate. A fatigue crack is transgranular fracture and so the crack surface is relatively smooth. All fractures, whether HE or fatigue, will have a final stage overload fracture which will be a rough lava rock looking appearance. This is simply due to the remaining part of the metal is no longer able to support the load and it fails by tensile overload. Tensile overload is officially called dimple rupture and that is where the rough lava rock looking surface description comes from.

I am sure many of you have heard someone say “It crystallized and broke.” As stated right in the very beginning of this lesson, all metals are crystal structure. What these people usually mean is the fracture surface has a crystalline appearance. If the crack is intergranular, like the HE crack above, it does have crystal facets. But the metal did not become crystallized! Intergranular failure can also be due to stress corrosion cracking (SCC). To have a SCC failure you need to have three things: 1) susceptible material, 2) applied tensile stress above a threshold amount, and 3) corrosive environment. Notice that this is similar to the HE in that you need the susceptible material and also tensile stress? The crack is also intergranular, but usually has a lot more corrosion due to the corrosive environment. HE cracks are fresh clean surface unless it has been exposed to something to make it corrode.

****

A list of topics potential future lessons include:

- nondestructive testing: magnetic particle, x-ray, ultrasonic, penetrant
- failure analysis, “why did it break?”
- Shot Peening and other surface conditioning
- Other suggestions?

Feel free to offer any other topics that you are interested in. I will try to explain the metallurgy behind it and any concerns you should be aware of. I will try to keep the technical content down low enough so you can follow, but have enough detail to still be able to understand why and how the metal behaves or reacts. Have fun reading and understanding this first lesson, feel free to ask any questions. Terry