Heat Treating Basics – A Primer

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There are a number of considerations that a heat treater or designer must consider. However, having a good basic understanding of what is going on or even some command of the terminology are valuable skills.

A couple of years ago, I took up Sporting Clays, which is a shotgun shooting sport where the target, a four inch round clay disc, is presented to you in two different ways over a course composed of maybe 10 to 15 different stations. Although I am still "developing" my skills, I have found this to be a fun and challenging sport. I have enjoyed it so much that for my birthday last year my wife presented me with a year's subscription to one of the sport's magazines. This too I have enjoyed, but it quickly showed me, with no lack of frustration on my part, how very little I really know about the sport. I couldn't tell you what the different target presentations are intended to represent, how competition is properly scored and for that matter what much of the terminology means.

In much the same way, when I was confronted early in my career with the process of heat treating fasteners, all but a few basic concepts that I remembered from my beginning Engineering Materials class were unknown and cloudy. As I gained more experience, asked questions, learned how parts were manufactured, saw the process and participated in the industry's technical community, I gained clarity and understanding. However, for those not normally engaged in technical activities or those new to the industry, I imagine that much about heat treating is shrouded in mystery. Why does one heat treat a fastener? How does it work? What is some of the important terminology? This article is intended to help give some simple answers to these questions and unwrap the mystery for those that have no reason or need to hold a metallurgy or engineering degree, but desire to know a little more about fasteners.

For the purposes of this article I will limit our discussion to basic carbon steel and carbon alloy fasteners. This covers the vast majority of fasteners, but certainly not all. Many specialty and highly engineered fasteners utilize more exotic materials that have special and unique metallurgy and often complicated mechanisms to improve physical properties. The bottom line is that this topic can be studied to great depths and there is much to know, even at the simplest level. This article will only touch on the most basic of these concepts.

Basic Scientific & Metallurgical Concepts

To understand heat treating, one must first understand some basic concepts of science and metallurgy. The first of these is to understand the concept of solid phases. To understand phases, first consider the example of H_2O (a simple water molecule). Water can exist as a liquid (water), gas (vapor or steam) or solid (ice). Each of these represents what is considered by scientists as different phases. Metals can also exhibit different phases although with steel there are only solid and liquid phases. Unlike water though, which only has one solid phase under all but the most extraordinary conditions and thus always exhibits the same physical properties in that phase, steel has several different solid phases.

This characteristic is referred to as being allotropic and means that although the constituents may be the same, those constituents structure and align themselves differently so that each solid phase exhibits characteristically different physical properties. To illustrate this, take for example the element carbon. Carbon has several solid phases such as graphite, which we all know is soft and black finding an excellent use in pencil lead, and another phase is diamond, which after being a "girl's best friend" is known for its incredible hardness and used the world over in cutting tools of all kinds. So a material can be composed of the same "ingredients", but exhibit radically different properties. Likewise, steel has more than one solid phase. These different solid phases are called allotropes and possess distinguishably different physical characteristics.

The second important concept to grasp is the thermodynamic principle of equilibrium. This means that given a sufficient amount of time, a system under proper conditions will eventually reach a constant state, where the temperature, pressure and composition of phases is unchanging. For example, consider a glass of ice water on a hot summer's day—the ice in the glass melts. This is a nonequilibrium situation. However, if this same glass of ice water is placed in a refrigerator at exactly 32°F, the ice will soon stop melting and a state of equilibrium results. In the same way, steel has specific equilibrium characteristics when one varies temperature and the percent of carbon mixed with the iron.

Figure 1 is a portion of the Equilibrium Iron-Carbon Phase Diagram. This looks very complicated and imposing. However, one should consider this and a second diagram, the TTT (Time-Temperature-Transformation) Diagram (seen in **Figure 2**) as the "road maps" to heat treating. If you study the Phase Diagram, you will see that the X-axis describes the percent by weight of carbon in the iron and the Y-axis describes temperature. The various lines on the diagram separate regions where different phases or combinations of phases are stable. It is important to recognize that this diagram only represents equilibrium conditions, but is very important for the heat treater or Engineer to understand as it defines the temperature or temperature thresholds to either make or prevent a phase change. This is critically important for a heat treater to know as it will define for example the differences in time and temperature settings for a hardening operation versus the settings for a stress relieving operation or the different process settings required to harden, say a 1022 steel from a 1045 steel.

Figure 2, the Time-Temperature-Transformation (TTT) Diagram, is equally important to the heat treater. The primary idea that it illustrates though, is the idea that all transformations of steel have some time dependency. In other words, the end result of the heat treating process (i.e., what transformation has occurred) will be highly dependent on cooling time. Looking at this diagram, one can see that the X-axis defines time and that the further along the axis one goes (i.e., slower the cooling process) the resultant is a set of transformations products different than the transformations that occur early along the axis.

Time is also important in other ways. Most of the heat treating processes require that parts start from a phase that has reached equilibrium conditions. This means for example that parts must be exposed to temperatures long enough to reach those temperatures all the way through. It is like putting a big bowl of food from the refrigerator in the microwave and heating it for only thirty seconds. Likely, that is just enough time to get the food around the edges warm, but leave the center cold. Therefore in heat treating, a process often must last long enough for a complete transformation to equilibrium to occur.

Additionally, a number of heat treating operations rely on the principle of diffusion. Diffusion is a time-dependent process where something is being added to or "driven" into the surface of the part. It is like the barbequed brisket that one can get in barbeque joints throughout the USA. These tasty cuts of meat are slowly barbequed for hours and sometimes even days. The resulting experience is a delicious cut of meat with barbeque flavor diffused throughout, obviously stronger at the outside and working its way into the center. If the cook, however, left them in the barbeque for only a short period of time, the experience would be completely different and the meat would be lacking that characteristic barbeque flavor and appearance. Diffusion is important when the designer wants or needs a strong hard surface to prevent wear or abrasion. Although these will be discussed later, case hardening, carburizing and nitriding are all examples of diffusion processes.

The final important concept to grasp is cooling. Although one naturally thinks about heat and high temperatures in a heat treating process, the act of cooling is actually far more critical to the end result. Basically, fast cooling results in harder steels and slow cooling in softer ones. Therefore, if a part is intended to be hardened, it will be necessary for a relatively rapid and aggressive quenching (process of cooling), whereas if the part is intended to be made softer, a process known as annealing, the quenching process will be slower and far

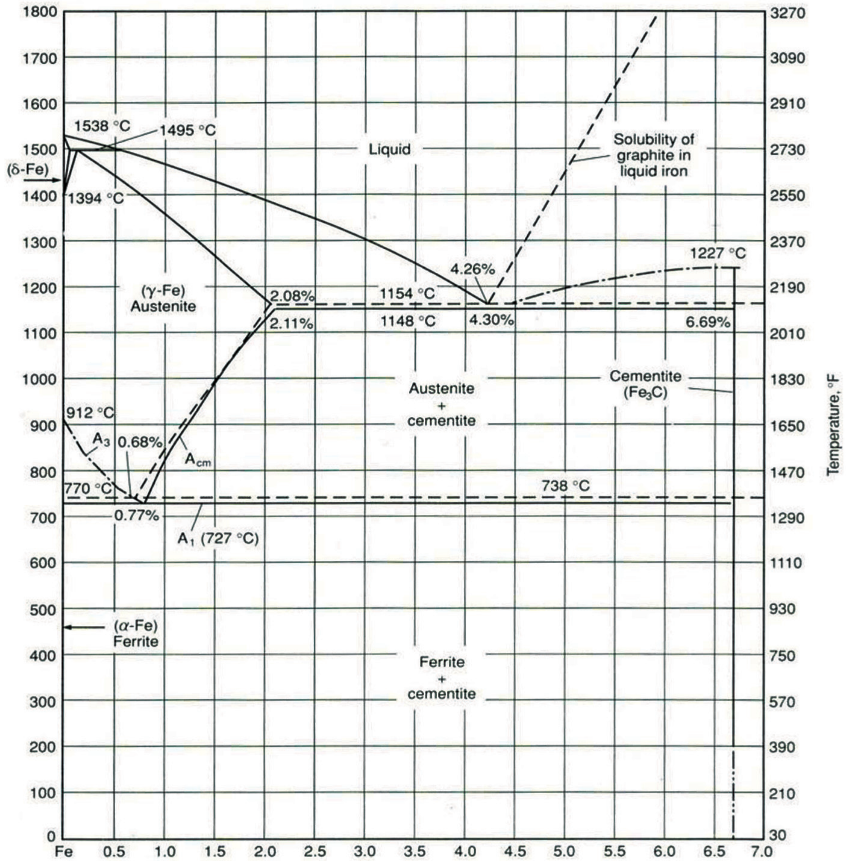

Fig. 1 — From the *ASM Handbook Volume 1, Microstructures, Processing and Properties of Steels,* Figure 1, p. 127, ASM International, Materials Park, OH, USA.

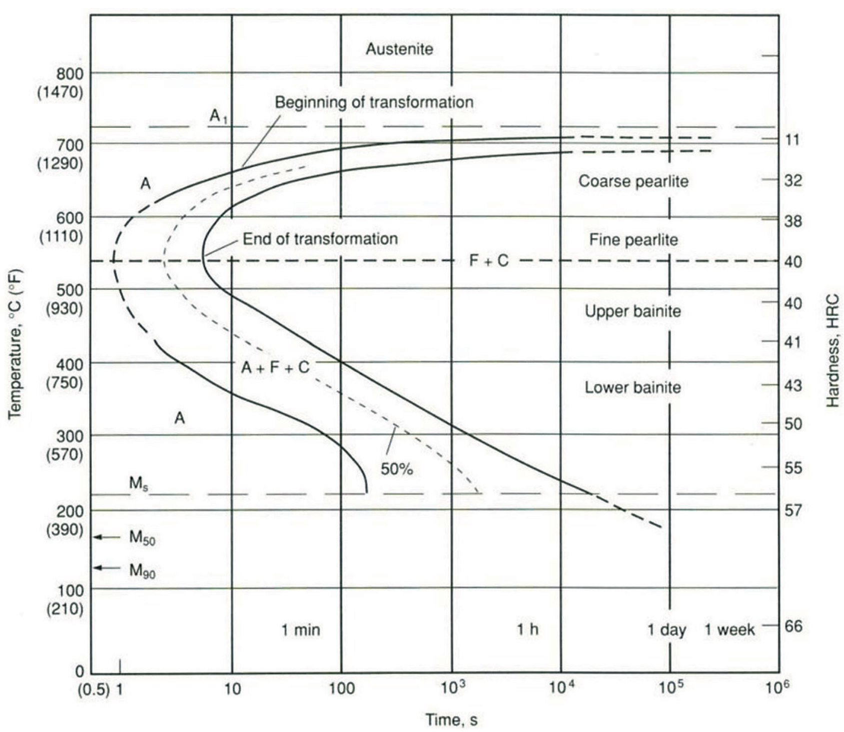

Fig. 2 — From the *ASM Handbook Volume 1, Microstructures, Processing and Properties of Steels*, Figure 4, p. 128, ASM International, Materials Park, OH, USA.

less aggressive (often just left to air cool.)

Understanding those principles will go a long way in having a fundamental understanding of what is happening during a heat treating process. However, before looking at the most common heat treating practices for fasteners, let me introduce a few important terms.

Atmosphere:

This is the make-up of what surrounds parts in the heat treat furnace. This surrounding gas is usually not just the air that is initially around the parts. Heat treating in such an environment can create dangerous oxides or be otherwise deleterious to the part.

Therefore, the heat treater will carefully choose the atmosphere surrounding the parts in the furnace, which is often a special gas or a vacuum, in order to protect them from losing important constituents or adding unwanted constituents to them.

For example, in a standard neutral hardening process, the atmosphere protects the parts from losing carbon from their surfaces, whereas in a carburizing treatment process, the atmosphere is actually rich in carbon so that it is adding carbon to the part surface (usually in order to make the surface harder).

Batch Furnace:

A batch furnace is one in which the parts are introduced in static (unmoving) loads. This usually means that parts are placed in wire baskets and loaded into the furnace where they stay until they are removed from the furnace or to quenching. For fasteners, batch furnaces are used for small loads, tiny parts, long parts and parts made of more exotic materials, but are rarely used to process large quantity, bulk, industry standard product.

Austenitizing:

Austenite is the common name for ϒ-iron (containing some dissolved carbon), which is one of the solid phases of steel. Austenite is the high-temperature solid phase of steel and only begins to transform to this phase at these high temperatures. It is important because many of the heat treating processes require austenite as the starting point from which to make their transformation.

For the heat treater, it is analogous to the dairyman's starting point of cream. The dairyman starts with cream, but depending on how he processes it, he can end up with whipped cream, butter, ice cream, sour cream or cheese.

Austenitizing is simply the term that is used to describe the heating of steel sufficiently long enough and at temperatures high enough so that the steel transforms completely into Austenite.

Belt Furnace:

A belt furnace is the most commonly used furnace type for fasteners.

Unlike a batch furnace, the belt furnace is designed to move the parts through the furnace on a slowly moving mesh belt. This is particularly advantageous for fasteners because of the productivity that can be achieved by running similar jobs back-to-back without having to bring the furnace down to change out loads and restart the heating process all over again.

Ferrite:

Ferrite is the common name for α-iron, one of the other solid phases of steel.

Ferrite is a lower-temperature phase of steel and is present at room temperature. It is neither hard nor strong, and would commonly be one of the prevalent structures in annealed steel.

Martensite:

Martensite is a nonequilibrium structure of steel that is formed when steel is rapidly cooled from austenite. Because it is formed very quickly, the process is not allowed to reach equilibrium, which is why it does not show up on the Equilibrium Phase Diagram. The only way for this steel phase to exist is through a process that "coaxes" it to form, in this case rapid cooling.

Martensite is hard and brittle when it is first formed. In fact, it is so brittle that in its initial transformational form, it really is not useful. Martensite must go through a subsequent heating process known as a temper to convert it to a useable condiiton.

Tempering:

Tempering is a process where martensite is reheated and held at a temperature below the austenite transformation temperature in order to relieve the internal stresses that result when martensite is formed by rapid cooling. Tempered martensite is not as hard as the initial untempered martensite, but by going through the tempering process it gains significant toughness and ductility (meaning simply that it is no longer brittle).

I'm not sure when the discovery of tempering first took place, but it is a discovery that revolutionized early sword and weapons manufacturing. Imagine going into battle with a brittle sword that would likely break the first time it struck something hard.

There is a great deal of history regarding the dominance of certain armies because of their artisan's superior steel-processing skills.

Common Heat Treating Processes

Although steel fasteners could theoretically receive any kind of heat treatment process available, the following heat treatment technologies are the most common processes for fasteners.

Annealing:

Annealing is the process of softening or making steel less hard. The annealing process is commonly employed on fasteners and fastener parts that subsequently must be upset or deformed such as on solid or semi-tubular rivets.

The annealing process may also be employed by fastener manufacturers that are required to soften a fastener part somewhere in the process stream in order to allow for further part deformation without causing cracking or other damaging effects.

In the annealing process, parts and components are fully austenitized and then they are allowed to slowly cool down in a controlled fashion. This is done either in air or in the furnace by slowly reducing the temperature. This results in a transformation to structures which are soft and easily deformed.

Stress Relieving:

Stress relieving is often confused with annealing. However, stress relieving and annealing are not the same.

Stress relieving is generally intended to relieve the internal stresses in a part that may be present resulting from the forming process. Unlike annealing, which starts with austenitized parts, stress relieving remains below the austenite transformation temperature and the heating process does not trigger a transformation, but relieves the stresses that may be in the internal structure.

Stress relieving is commonly found on fasteners and parts that subsequently get deformed, but might require more strength than would be found in an annealed fastener part.

Normalizing:

Normalizing is an annealing process that is rarely used on fasteners. However, it is commonly used on castings. The primary intent of the normalizing process is to provide a homogenous microstructure.

Hardening:

This process is often referred to as neutral hardening, through hardening or quench and temper. This is the most common process employed in heat treating fasteners, and is used to strengthen parts after forming. Hardening is often referred to as through hardening because the hardness and strength are intended to be consistently the same throughout the entire part.

With hardening, there is a wide range of what is possible, but results will vary significantly depending largely on the size of the parts and the steel from which the fasteners are produced.

When fasteners are referred to as meeting Grade 5 or Grade 8 or Property Class 8.8, 9.8 or 10.9, these are indicators that the parts have been hardened through heat treating to achieve these stronger properties.

In the hardening process, parts are austenitized, rapidly quenched (usually in oil), and then tempered.

Induction Hardening:

Unlike all the other processes described, which treat the entire fastener, induction hardening is selective. It is a common practice on self-tapping screws for steel where the thread forming point must be very hard, but the portion of the fastener in service requires greater ductility. This is commonly found on automotive anchor bolts for seat belts and seat tracks.

Parts are often through hardened first and then induction hardened. To induction harden a part, it is passed through an induction coil (basically a very intense, rapidly changing magnetic field), which locally heats that part of the fastener above the austenite transition temperature, then it is quenched with a squirt of water or dunked into a coolant tank, and then it is tempered. The result is a part with a selectively hardened zone.

Carbo-Nitriding (Case Hardening):

This is perhaps the second most common heat treating process for fastener parts. Carbo-nitriding allows a low-carbon steel part to receive a harder outer shell. This is particularly advantageous for self-tapping screws where the threads must be stronger and harder than the material that they are tapping into.

Case hardening is a diffusion process. This means that during case hardening the parts are exposed to an atmosphere that is rich in carbon and nitrogen. These carbon and nitrogen constituents only have time to diffuse into the surface of the parts, which results upon completion in a hard outer shell and a softer core.

The carbo-nitriding process involves austenitizing in the above-described enriched atmosphere, with quenching and tempering.

Carburizing:

This is a diffusion process where the atmosphere is enriched with carbon, which diffuses into the surface of the part. Like case hardening, parts are austenitized, quenched and tempered. The resulting product has a harder outer shell.

Nitriding:

Nitriding is a diffusion process of nitrogen. Unlike the first two diffusion processes described above, nitriding is done at temperatures below the critical austenite transformation temperature.

Nitriding can produce a very hard outer surface, but is not a process commonly used on fasteners.

Ferritic Nitrocarburizing:

This is a low-temperature diffusion process of carbon and nitrogen that provides a very thin iron epsilon layer, often known as the “white layer”. This layer, although thin provides good wear properties.

Although the ferritic nitrocarburizing process is more commonly used on thin-walled/thin items that would be prone to distortion under normal process parameters, it is not uncommon to find these processes specified on specialty fasteners that act as a pivot or provide some other type of wear surface.

In Summary

These are the basics. There are quite a number of other considerations that a heat treater or designer must consider. However, having a good basic understanding of what is going on or even some command of the terminology are valuable skills.

There are a number of excellent resources available for further exploration or a deeper dive into this topic. There have been many articles published on these topics including excellent and more in-depth pieces from several regular contributors to this journal.

One of the best reference guides for its simplicity and conciseness is **Atif Odeh’s** “Metallurgy and Heat Treatment The Pocket Book”.

Additionally, there are short courses and technical seminars as well as video classes that are available from multiple sources.

In fact, my company, **NNi Training and Consulting**, offers a much more detailed course (conducted in-person) on this topic that is customized to a customer’s informational requirements.

For additional information, of for additional discussion, contact the author at NNi Training and Consulting via email at *laurence@nnitraining.com*. **FTI**