Fundamental Principles of Heat-Treating Steels

by Richard D. Sisson, Jr. and Daniel H. Herring photo provided by Chen Nan Iron Wire

eat-treating is a process that is critical to the fabrication of steel fasteners. It is a necessary process in order to achieve the mechanical properties. Heat-treating is typically conducted after the forming processes and before any coating or finishing processes. Heat-treating may be done by the manufacturer or outsourced to a commercial shop. The equipment necessary to effectively heat treat steel fasteners includes well controlled furnaces with temperature control, atmosphere control, quenching tanks, and cleaning equipment.

The steel heat treatment process consists of heating the steel fasteners into the Austenite range, that is to a high temperature 840°C~980°C (1,550°F~1,800°F), in which the steel becomes "red hot" for some time. Following the heating process, the parts must be cooled (quenched) rapidly usually in a liquid media such as oil or water. When quenching has finished, the next step is to re-heat (temper) the quenched parts at a temperature lower than that which was used to harden the parts 200°C~480°C (400~900°F).

The critical heat-treating process parameters are time, temperature, atmosphere, and cooling rates. In this article the fundamental physical metallurgy of steels will be presented for each step in this important process. Future articles will talk about each aspect of the heat treatment operation.

The Iron - Carbon Phase Diagram

Pure iron can exist with two crystal structures. At temperatures below 912°C (1,675°F), the crystal structure of iron is body centered cubic (bcc) and is referred to as Ferrite (α). At temperatures between 912°C (1,675°F) and 1,394°C (2,540°F) the crystal structure of iron is face centered cubic (fcc) and is known as Austenite (γ). Above 1,394°C (2,540°F) and below the melting point of pure iron 1,538°C (2,800°F), iron returns to bcc and is designated as delta (δ) Ferrite. Steel can be heat treated as a result of this Austenite to Ferrite phase transformation.

Iron can form a solid solution with carbon to produce steel. The carbon atoms dissolve into the solid by filling the interstitial sites of the fcc and bcc crystals. Due to the size and shape of these interstitial site the fcc iron can dissolve up to 2.14 wt% C while the bcc iron can only contain 0.022 wt% C. This 100-fold difference in carbon solubility in the two iron crystal structures is also necessary for the heat treatment of steel.

The Iron - Carbon phase diagram is presented in **Figure 1**. Some of the key features of the phase diagram were described above. A phase diagram is a map of the phase or phases that exist in equilibrium as a function of temperature and composition. For steel the composition is given in wt% carbon and the temperature is in either Celsius or Fahrenheit. Typical steels contain between .10 and .80 wt% carbon.

Pearlite Formation

Let's consider steel that contains 0.76 wt% carbon. As seen on the phase diagram, if this steel is heated to 800°C (1,470°F), the fcc Austenite (γ) solid solution exists. However, if the Austenite is cooled to below 723°C (1,333°F) a phase transformation will take place to form the iron carbide (Fe3C) also known as cementite and the bcc Ferrite (δ) solid solution containing less than 0.02 wt% carbon. At 723°C (1,333°F) a three-phase equilibrium exists as seen on the phase diagram. Austenite is in equilibrium with Ferrite and Cementite at 723°C (1,333°F).







When this phase transformation takes place on relatively slow cooling a microstructural component called Pearlite is formed. Pearlite consists of plates of Fe3C in a matrix of Ferrite (α) as seen in **Figure 2**. Pearlite is formed from Austenite containing the eutectoid composition of 0.76 wt.%C. This microstructure develops as a result of the decomposition of Austenite by nucleating carbide plates first and then the Ferrite on the sides of the carbide plates.

Steels that contain less than 0.76 wt.%C are called hypoeuctoid steels. As seen in the phase diagram, when a hypoeuctoid steel containing 0.40 wt.%C is heated to 900°C (1,650°F) Austenite forms. When this steel is slowly cooled the first new phase (also called the primary phase) is Ferrite. During this cooling to 723°C (1,333°F)



a microstructure of primary Ferrite and Austenite is developed. Upon cooling below 723°C (1,333°F) the Austenite, which now contains 0.76 wt%C is transformed to Pearlite. The resulting microstructure of this alloy will consist of approximately 50% primary Ferrite and 50% Pearlite, as seen in **Figure 3**.



Steels containing more than 0.76 wt.%C are called hypereutectoid steels. As seen in the phase diagram, when a hypereutectoid steel containing 0.90 wt.%C is heated to 900°C (1,650°F), the Austenite solid solution forms. When this steel is slowly cooled the primary phase is iron carbide (Fe3C). Upon cooling below 723°C the Austenite, which now contains 0.76 wt.%C transforms to Pearlite. The resulting microstructure of this alloy will consist of approximately 2% primary carbide and 98% Pearlite as seen in **Figure 4**.

Time Temperature Transformation (TTT) Diagrams

The phase transformations described above are diffusion controlled and occur by nucleation and growth. The rates of these transformations are a function of temperature and steel composition and can be described with time - temperature - transformation



diagram for the eutectoid steel as seen in **Figure 4**. This particular diagram presents the rates for isothermal (constant temperature) transformations of a eutectoid steel. In these diagrams the y-axis is temperature and the x-axis is time. In this instance the logarithm of time is used. As seen on this diagram at temperature above 723° C (1,333°F) the Austenite phase is always stable. However, when this steel is cooled very rapidly to 600°C (1,100°F) the Austenite becomes unstable and will over time transform to Pearlite. As seen in **Figure 4**, after 2~3 seconds the Austenite starts to transform to Pearlite, after 6~7 seconds the transformation is 50% complete (i.e. 50% Austenite and 50% Pearlite), and after about 15 seconds the transformation is complete, meaning 100% Pearlite is all that remains.



For this eutectoid steel, when rapidly cooled to a temperature below the nose of the TTT curve a slightly different type of transformation occurs, it will result in the formation of Bainite. Similar to Pearlite. Bainite consists of a mixture of Ferrite and carbide. However, the morphology is finer and can have a more feathery or acicular appearance. As seen in Figure 4, after rapid cooling to 400° C (750°F), the Austenite is unstable, after about 7 seconds the Austenite starts to transform to Bainite, after about 80 seconds the transformation is 50% complete and after about 200 seconds the transformation to Bainite is 100% complete. These TTT diagrams are available for a wide variety of steel compositions.

As presented in these TTT diagrams the transformation from Austenite to Pearlite, Bainite, primary Ferrite or carbide takes time. These transformations are diffusion controlled and diffusion takes time.

Martensite Formation and Tempering

When Austenite quenched to room temperature a new phase transformation can occur. The fcc Austenite can transform to Martensite a body centered tetragonal (bct) phase. This reaction is not diffusion controlled and takes place by a shear-type transformation and is solely a function of temperature, not time. The as-quenched Martensite is extremely hard and brittle. **The hardness of the Martensite is dependent on the carbon content of the Austenite in the steel**. The Martensite and the Austenite it came from have the same chemical composition.



As quenched Martensite is too hard and brittle for most practical uses, however it can be heat treated to recover some toughness and ductility. This heat treatment is known as tempering. Tempering consists of re-heating the Martensite to a temperature between 200 °C (400°F) and 400°C (750°F) for several hours. During this heat treatment carbides precipitate in the Martensite matrix. The result of this transformation is an increase in the toughness of the steel by the carbide precipitates as well as the decrease in the carbon content of the Martensite. In fact for some steels, the tempering process of an alloy may increase in strength and toughness.

Important Process Parameters

As stated above, the important process parameters for the high temperature heat treatments to form Austenite are temperature and time. The temperature must be within the Austenite single-phase region as seen on the phase diagram but not so high to cause the grain size of the Austenite to become too large. Austenite grains that are too large can cause a variety of problems including fatigue. The time for the parts in the furnace must be long enough so that the entire furnace load achieves the furnace temperature. This time will depend on part size as well as total part load. In addition, some extra time is needed to transform the Ferrite to Austenite and dissolve the carbides in the microstructure. Holding the parts at temperature will cause grain growth in the Austenite as well as an undesirable waste of energy and money.

To avoid carburizing or decarburizing, the carbon potential of the atmosphere in the high temperature furnace must be closely controlled. Typically, the atmosphere in these furnaces is controlled with an Endothermic gas generator. The details of atmosphere control will be a subject of a future article.

The next step in the process is cooling. The cooling rate must be controlled to achieve the desired microstructure. If a pearlitic structure is specified, the cooling rate must be slow enough to cross the Pearlite start and finish lines. If Bainite is what is desired, the rate of cooling must be fast enough to miss the nose of the TTT curve, and then be held at a temperature above the martensitic start line for a time long enough to cross both the start and finish lines of Bainite formation. If tempered Martensite is desired, the steel must be quenched fast enough to miss the nose of the curve and cross the Martensite start and finish lines. The martensitic steels can experience cracking and distortion if quenched too quickly. The control of cooling rates will be a topic for a future article.

For tempering the important process parameters are temperature and time. The temperature must be selected to control the size and distribution of the carbides that precipitate during the tempering process. The time must be long enough to heat the entire load to the desired temperature. In addition, time is needed for the nucleation and growth of the carbides to form the tempered Martensite.

Conclusion

Heat-treating steel fasteners to achieve the desired microstructure and properties can be achieved by control of the important process parameters of temperature, time, and cooling rates. Knowledge of the fundamental physical metallurgy of the phase transformations in steels is critical to understanding the importance of these process parameters.

References

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