Chemistry and Heat Treatment

The Recipe for Steel Success

By Andy Kultgen

If you stop and take a look around your shop at your equipment and tools, and maybe the walls and beams of the building itself, you are bound to see dozens or hundreds of individual metal components. Given the tough, rugged environment of the construction industry, most of those metal components are steel or iron. The tasks we use those components for may vary quite widely, even though they may be very similar materials. Some materials may need to be strong, tough, and flexible, like the frame of your truck. Others may need to be rigid and very hard, to resist wearing out, like the races of a wheel bearing, or the cylinder walls of a hydraulic cylinder or material cylinder of a wet-mix shotcrete pump. Other components may need to be incredibly tough and resistant to cracking, like the head of a hammer. All those components can be made from very similar recipes of steel, but the difference lies in minute changes in the amounts of carbon and other alloying elements, and the heat treatment.

INTO THE CRUCIBLE

Steel refers to a specific range of recipes, called chemistries, of iron alloys. What sets this group of materials apart from other iron alloys is the amount of carbon present in the metal. Steel generally ranges from almost zero carbon up to about 2% carbon, in what are called high-carbon steels. The presence of trace elements can have an enormous effect on the properties of the steel. The properties of steels are closely related to the crystalline structure the steel takes when cooled from molten to solid. Just as water has a crystalline structure when it freezes, so does steel. The crystalline structure is influenced by the chemistry and how quickly you cool and solidify the steel. Many steels for general use are primarily iron and carbon. Other steels, known as alloy steels, have additions of alloying elements.

Common alloying elements are manganese, nickel, chromium, molybdenum, and vanadium; however, there are many more possibilities. These elements, in the right amounts, increase desirable properties, such as toughness, strength, or corrosion resistance. Some elements, such as sulfur and phosphorus, are limited to a maximum amount, as they generally weaken steel. Many standard chemistries of steel are defined by various specifying bodies. They list the acceptable ranges for various elements and the known physical properties for steels with that chemistry. You may have heard of these specified chemistries, or grades, of steels before. In the United States, they are dictated by SAE and ASTM International and have names like 1018, 4140, or 316. The 4100 series of steels have chromium and molybdenum additions, so are commonly called Chromoly steel. The 316 stainless steel resists corrosion because of the addition of chromium and nickel.

Fig. 1: Chemistry sampling: (a) taking a sample—a furnace operator takes a sample of molten metal from the furnace. He will pour the metal into a water-cooled mold to quickly make a sample for the quality control laboratory; and (b) spectrometer—a technician places the metal sample cylinder, or button, on the sample stage of the spectrometer. This machine will analyze the chemistry of the metal in just seconds, allowing the technician to approve the chemistry of the sample or inform the furnace operator how much alloying elements to add to this melt (batch) of metal

(Photos courtesy of Alliant Castings)

Grade	Allowable limits, % by mass													
	Carbon		Manganese		Phosphorus	Sulfur	Silicon		Nickel		Chromium		Molybdenum	
	Min.	Max.	Min.	Max.	Max.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
4140	0.38	0.43	0.75	1.00	0.04	0.04	0.15	0.35	—	—	0.80	1.10	0.15	0.25

Fig. 2: SAE chemistry specification—an example of a chemistry specification for a certain grade of material. In this case it is SAE 4140 alloy steel, a common alloy steel, often called Chromoly steel

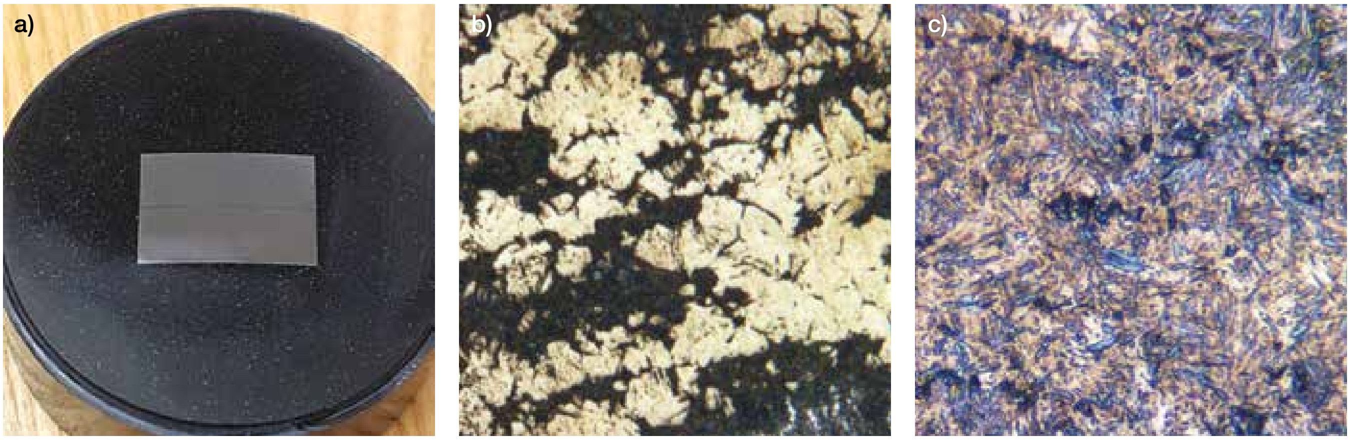

Fig. 3: Metal structure: (a) sample mount—a small sample of steel is encased in phenolic resin to hold it securely. To examine the steel crystalline structure, the sample is etched with a nitric acid solution to dissolve one type of crystalline structure and expose another. The sample cylinder in the photo is 2 in. (50 mm) in diameter. This steel sample was heat treated with localized heating and quenching, so there is both martensite, ferrite, and pearlite present. Both accompanying microstructure photos were taken from this sample; (b) perlite/ferrite—a mixture of ferrite (the light areas) and pearlite (the dark areas); and (c) martensite—tan areas. Martensite crystals grow in branching plates, resembling frost on a window

HEAT TREATMENT THEORY

A single chemistry of steel can form several different states depending on how it is heated and cooled. The different states can be distinguished under a microscope; they have distinct crystalline structures in different quantities. These different crystalline structures lend different physical properties to the steel. To heat treat a steel, the material is heated up above its critical temperature, but below the melting temperature, where the material's structure is called austenite. Cooling the material slowly will result in a mixture of structures called pearlite and ferrite; this is known as annealing or normalizing, depending on the exact parameters. Cooling quickly results in a mixture called martensite and is known as quenching. Quenching is typically done by immersing the component in a water or oil bath. Pearlite tends to be softer and more ductile, so the steel will bend and deform instead of breaking but will not be as strong. Martensite is harder and more brittle; steel in this state will be harder and stronger but will fracture more easily.

Typically, a material will be tempered after quenching. Tempering involves heating the quenched steel to a temperature below the critical temperature. This relieves stresses in the martensite, reducing the likelihood of cracks growing through the material, but does not change the martensite back into austenite. The result is a martensitic steel that is still strong and hard, but less prone to cracking. Each chemistry of steel has an Isothermal Transformation diagram that manufacturers can use to know how quickly to cool the steel to achieve the desired crystalline structures.

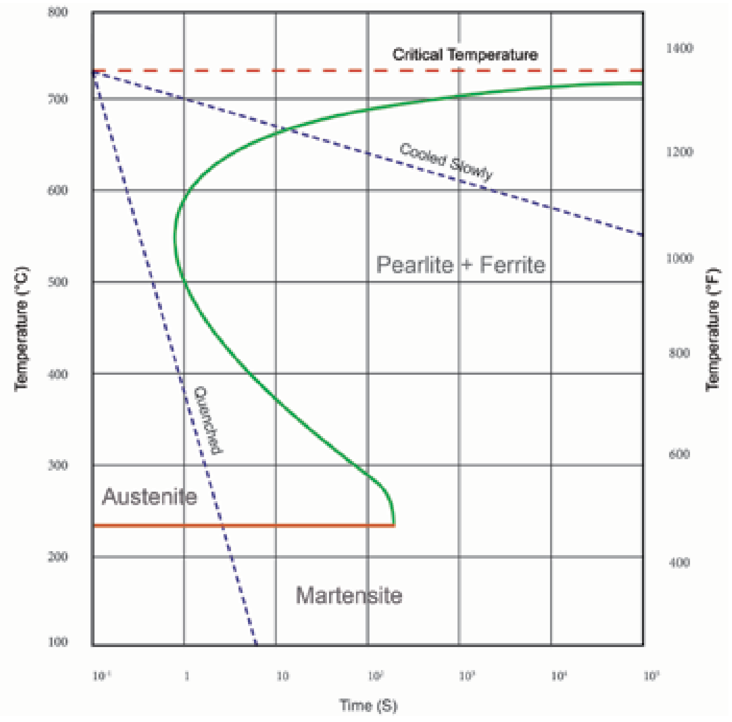

Fig. 4: TTT diagram—this Isothermal Transformation diagram can be used to determine how quickly to cool a steel or other metal when heat treating. The steep line shows a metal that was quenched, cooled from over 1300°F (700°C) to room temperature in a matter of seconds, and would be in a primarily martensite structure. The less steep line shows a metal that was cooled from the same temperature slowly, over several hours. This metal would be in a mixture of pearlite and ferrite structures

There are more states of crystalline structure for steel and iron alloys than covered in this article and more advanced methods of heat treating, many of which are employed by contemporary pumping equipment suppliers. For wet-mix concrete pumping, high hardness results in better wear characteristics, but too high of hardness results in a brittle component that cannot tolerate rough handling, such as being hit by a hammer or dropped on the bed of a truck.

WHAT IF I WANT WEAR RESISTANT AND TOUGH?

There are many cases where a component should have a hard surface to resist wear but should be tough as well. Martensite is hard and resistant to wear but is brittle and prone to cracking. A pearlite and ferrite mixture is ductile and resistant to cracking but isn't very hard and will wear quickly. The types and quantities of each crystal structure present are defined by the chemistry of the steel and how quickly it is cooled. To get differing material qualities in different areas of a component, you need to either vary the chemistry or the heat treatment within the component.

TARGETED AREA HEAT TREATMENT

If a component is a shape that allows part of it to be quenched while the rest is allowed to cool slowly, it can be heated up and quenched in just one area. Add tempering afterward and you have the process often used for hand tools, power tool bits, and a wide variety of other components where you need one end to be hard, to keep an edge or point, and the rest of the part to be tough and durable.

TARGETED AREA CHEMISTRY

If the component cannot be quenched in only the area that should be hardened, another option is to change the chemistry in that area. The amount of martensite is generally related to the amount of carbon in the steel. A component made of a steel with low amounts of carbon throughout, but with high levels of carbon just on the surface, could be quenched and tempered to produce a part with good toughness and ductility through most of the thickness, but high hardness right at the surface. This process is called case hardening. By heating a component above the critical temperature where it changes to an austenite structure and exposing it to a high-carbon environment, carbon molecules will soak into the steel. The higher the carbon amount in the environment and the longer the steel is exposed will result in more carbon soaking deeper into the steel. This process can be done with nitrogen as well as carbon; they are known as nitriding and carburizing, respectively.

HEAT TREATMENT PRACTICE

There are several ways to heat treat components to be used for concrete pumping—the requirement is just that the steel be heated above the critical temperature and then cooled at the right rate to develop the desired crystalline structure. A common practice is to batch heat treat. In batch heat treating, the material is placed into an oven and heated to the desired temperature. Heat treating ovens are commonly powered by fossil fuels, usually natural gas. If an annealed part is desired, the heat for the oven is turned off and the load is allowed to cool very slowly inside the oven. If a

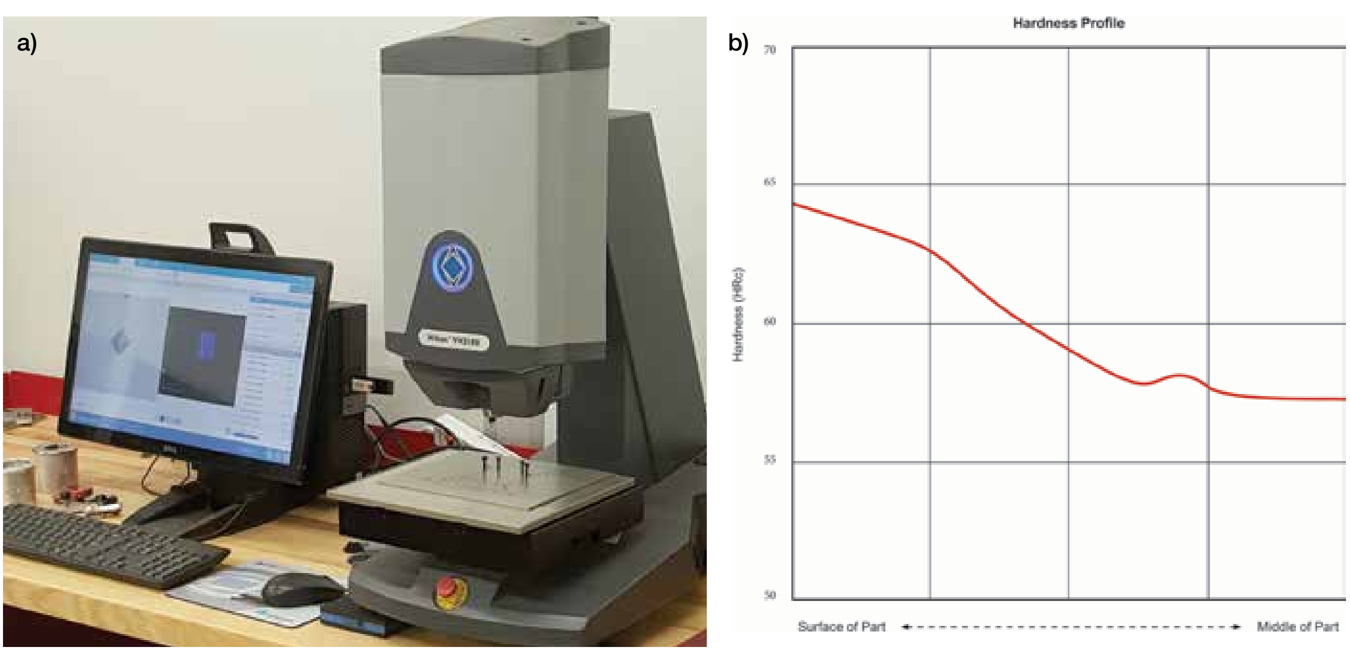

Fig. 5: Hardness check: (a) microhardness—this machine can measure the hardness of samples in very small increments. This allows technicians to very closely monitor the results of heat treatment, especially in cases of case-hardening or targeted heating and quenching; and (b) hardness gradient—this is a plot of hardness values of a cross section of a steel part. The plot begins at the surface of the part. You can see this part was case-hardened, resulting in a very hard surface layer and decreasing hardness throughout the middle of the part. This part is used in concrete pumping and has a very high surface hardness to resist abrasion

hardened part is the goal, the load is removed from the oven and quenched into a water or oil bath.

This process can be used from continuous processing as well, by feeding a continuous flow of materials into the oven, allowing the material enough time to come up to temperature, and then feeding the material into a quench tank.

In some applications, continuous processing can take advantage of a directed heating method called induction. Induction applies electricity to coils to produce magnetic fields, which rapidly switch polarity. Electrically conductive materials that are close to the fluctuating magnetic fields will have electric current induced within them. The material's resistance to the flow of electricity causes the material to heat up. Because the magnetic field only affects electrically conductive materials, the energy is focused on heating the metal object and is not wasted heating other things. Once the material reaches the critical temperature, it can be quenched to create the hardened structure.

A common method of carburizing and nitriding is gas carburizing/gas nitriding. Parts are heated in a sealed oven with a controlled atmosphere rich in either carbon or nitrogen. Commonly used gases are carbon monoxide for carburizing and ammonia for nitriding, but several other options exist. Once the parts have soaked for long enough, they may be removed from the oven and quenched and tempered as desired to reach the right hardness and toughness levels.

Fig. 6: Heat-treat oven—a load of castings is pulled out of the batch heat treating oven. This alloy is quenched with forced air, not a water or oil bath. They are positioned below powerful fans, which will blow air over the castings, cooling them rapidly. The pieces of reinforcing bars are used to keep the castings from contacting one another, which would result in uneven heating and cooling
(Photo courtesy of Alliant Castings)

This summary of materials and heat treatment for steel barely scratches the surface of the fields of metallurgy and material science. Ancient people created iron tools thousands of years ago, figuring out how to make material that fit their needs by trial and error. Now, these concepts are taught to engineering students early in their careers, and engineers and material scientists can do things that couldn't be imagined a few decades ago with a wide variety of materials. Next time you are holding a wrench that says Tempered and Vanadium, you know that the steel chemistry included vanadium to increase the strength and hardness and it was tempered after quenching to make a hard part that is resistant to wear but has a decreased likelihood of cracking. Suddenly that plain old wrench doesn't seem so plain anymore.

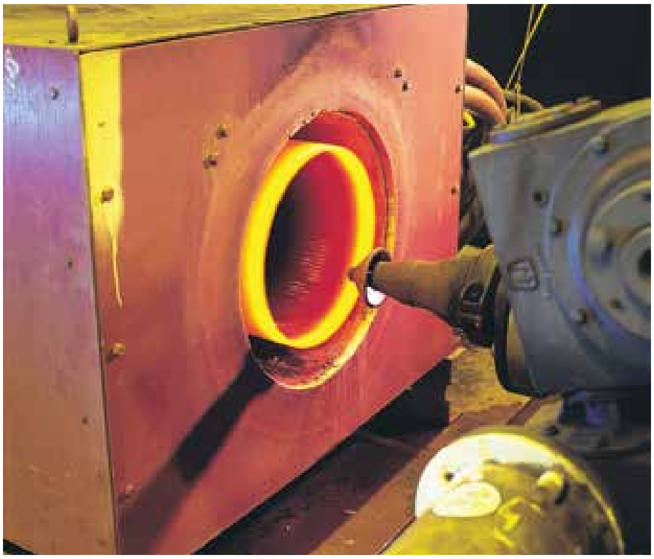

Fig. 7: Induction pipe—a steel pipe emerges from the stationary induction heating coil. The pipe travels quickly through the water-cooled coil, which is protected inside the orange box. Having been heated to over 1600°F (875°C), the pipe immediately passes over a smaller pipe, called a lance, seen in the center-right. Water floods out of the lance, quenching the pipe, resulting in a very hard pipe that is effective at resisting abrasion

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