500° F. Embrittlement In Steels
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Several years ago, a very good and nationally known gunsmith that resides in Colorado, told me that the screwdriver bits he made were breaking at a bothersome rate. I asked him about his heat treatment. He said he heated them to a good red color with a torch, quenched in oil, and tempered with the torch. I suggested that he temper them in his kitchen oven at 450° F. to 475° F. A few months later he told me that his oven-tempered bits were holding up well.

What was happening with those torch-tempered screwdrivers? The answer is 500° Fahrenheit embrittlement (500-F-E), or what some metallurgists call tempered martensite embrittlement.

What is 500-F-E? First, let's run briefly through the heat treating process. You can take a work piece of almost any plain or alloyed carbon steel, heat it to 1,400°-1,500° F. This heating process causes the face-centered crystalline austenite grains to form and the carbon that is present, migrates into the spaces between the iron atoms in the austenite. The work piece is then quenched in oil or other medium so the austenite transforms almost instantaneously to body-centered martensite grains. Inside these grains is where the carbon atoms now lie. They lie in spaces between the iron atoms because the body-centered martensite grains are really too small for them. This process gives a very strong and hard, but brittle microstructure to the steel.

So far so good. Now we have to heat and temper this brittle martensite to reduce that brittleness and give us a useful metal. Tempering is a complex process in which the heating causes two major things to happen.

First: Carbon atoms tend to migrate from those cramped spaces in the martensite grains toward grain boundaries, where they combine with the iron atoms and with some alloying elements such as chromium. This alloying process forms carbide grains that are called cementite by metallurgists.

Second: Martensite grains tend to transform to the more stable form of iron called ferrite. Ferrite also has a body-centered packing of the iron atoms. This growth of the carbide grains and the transformation of martensite to ferrite combined with gradual heating makes the steel softer, less strong, and less brittle, but it also makes it tougher.

I define toughness as the ability of a metal to deform plastically, under increasing load, prior to fracture. But Mother Nature threw us a curve ball in the tempering process; the decrease in brittleness (or increase in toughness) that occurs with increasing temperature stops at about 500° F., and the steel actually becomes more brittle as 600° F. is approached. Heating it to higher temperatures again causes brittleness to decrease, and by about 700° F., the steel has regained the toughness it had at 500° F. Continued heating above 700° F. will make the steel progressively softer, tougher, and less strong.

So, we have a region in tempering from about 500°-700° F. where a steel is more brittle than steel tempered at lower or higher temperatures. This is 500° F. embrittlement. In industry, steels are tempered either below or above this 500° F.-700° F. range.
The cause of 500-F-E is only moderately understood, in spite of much study. It apparently is largely due to growth of very fine, brittle carbide grains at or close to the grain boundaries of martensite and ferrite. High contents of phosphorus and some other minor elements also may promote it. Most of our common high-strength steels, like plain carbon 1050 to 1095 and alloys 4130, 4040, 0-1, W-2, etc., show 500-F-E.

We can demonstrate 500-F-E diagrammatically using results of the Charpy V-notch test versus temperature. The Charpy impact testing machine uses a 1 cm square, cross section of the steel that has a transverse notch or groove cut in its center. This test bar rests on anvils 5.5 cm apart in the tester, with the notch facing downward. Heating or cooling jackets are used to bring the test bar to any desired temperature. A swinging pendulum striker mechanism impacts downward on the center of the bar, and the operator records the energy required to fracture it. Energy values typically are given in foot-pounds (fall of a 10-pound weight from a height of 1 foot gives 10 foot-pounds, and so on). If Charpy V-notch energy values are determined then graphed for a steel test bar from room temperature to more than 700° F., we obtain curves like those shown in the chart for three, common, chrome-moly steels.

So there you have it, the cure for steel embrittlement is to avoid that 500° F.-700° F. interval when tempering your steel items!