A Short Guide to Heat-Treating

by Josh Earl

To show how the theory looks in practice, I thought I'd describe how I go about heat-treating a typical blade. I work with 1084 steel, which is pretty similar to what we've been discussing but isn't widely available. There's one guy who sells it to bladesmith types. It has (you guessed it) .84 percent carbon.

My Tools

My heat-treating equipment is as follows:
- Small forge made out of two refractory bricks, with a JTH7 propane plumber's torch serving as a heat source
- High-temperature thermometer and temperature probe
- A 6" piece of 2" iron pipe
- 1 gallon of specially formulated quenching oil (Parks #50)
- A hot plate from Wal-Mart
- An meat thermometer (the kind with a steel probe)
- A thrift store toaster oven
- Tongs, gloves, miscellaneous tools

You can get by without some of this stuff, but each tool plays an important role. Heat-treating is all about controlling variables. Knowledge is your biggest asset, but better equipment will allow you to put that knowledge to good use.

The Process

After I've forged a blade blank to shape and ground it close to its final dimensions on my belt grinder, I'm ready to heat-treat it. Heat-treating is the most important step in making a blade. The grinding and polishing won't matter much if the steel is poorly heat-treated.

I get everything set up before I start messing with hot steel. First, I put the iron pipe inside my forge. (It acts as a diffuser for the intense heat of the fire, protecting the blade and allowing it to heat more evenly.) Then I light the torch and crank open the propane a bit. It'll take a few minutes to get up to temperature. I get out my thermometer and high-temp probe and put the tip of the probe into the pipe. Now I can control the temperature in the pipe by manipulating the propane flow, and the thermometer will tell me how I'm doing.

I then set up the hot plate on the floor near my forge, with my container of Parks #50 quenching oil on the burner. I put the meat thermometer in the oil and turn on the hot plate. This preheats the oil to 130 degrees F, which works well for the steel I'm using.

I set up my toaster oven on the work bench and set it for 400 F. I also like to put some newspapers down on the shop floor to catch oil drips.

Once everything is set up and the forge has reached about 1500 F, the fun begins.

Normalizing

I start the heat-treatment process with a step that I didn't mention in my previous post. All the heating and cooling during the forging process, plus the heat and strain of the grinding, leave the blade blank with some internal stresses. To get rid of those stresses and set up the internal structure of the steel to respond to the heat-treatment, I do a step called "normalizing."

Normalizing involves heating the steel up past its critical temperature, then allowing it to cool slowly in still air. It's not annealing, which involves slowly cooling the blade over a period of hours. Normalizing takes less than 20 minutes, start to finish.

I stand the blade on its spine in the forge, inside the pipe. The temperature probe sits near the edge, allowing me to keep close tabs on how hot the steel is getting. When the steel first goes into the forge, the readout on the thermometer drops quickly—it's like putting an ice cube in water. When the temperature reaches its previous level and stabilizes, the steel is the same temperature as the inside of the pipe.

This is where I run into a problem. My forge doesn't heat very evenly right now. Even with the pipe, there is still a hot spot in the middle. I have to compensate for this by keeping it a little hotter than I really want to and moving the blade into and out of the hot spot. Overheating slightly gives me a little leeway to play with. If the tip gets 50 degrees hotter than I want, it'll cool a bit when I shift the blade to heat the heel. I don't like having to do this, and my next forge will be much more even.

Because of that, don't take the temperatures I'm listing here too seriously. They're working pretty well for me right now in my setup, but they may be off base with better equipment.

To normalize, I heat the steel to 1450 F, hold it there for a couple of minutes, then take it out of the forge and allow it to cool until it's black again. This takes about two or three minutes. The color is all gone by the time the steel reaches about 800 F or so, and then it's back into the forge again. I normalize three times.

By heating above critical and then cooling, I'm allowing the steel to recrystalize with each cycle. This refines the internal structure of the steel and relieves any residual stresses from the hammering and grinding. Normalizing helps prevent warping and cracking, and it allows the steel to harden more fully when it's quenched.

Hardening

After the steel has cooled to black for the third time, it's time to harden it. Normalizing usually takes about 15 minutes, so my quenching oil has reached my target temperature of 130 F. The forge is holding a steady temperature of about 1450 F. (I usually have to keep tweaking it, actually. I turn the gas up and down a bit, and move the torch closer to and farther away from the fire hole on the side. But I can hold it within 20 degrees if I baby sit it.)

I pop the blade in the pipe one more time and allow it to come slowly up to temperature. Heating slowly is desirable because it allows the interior of the steel to heat up, not just the outside.

I use my thermocouple to judge the hardening temperature, but there are a couple of other clues that can be useful. Iron looses its magnetism at 1414 F, and on 1084 steel this is close to the correct hardening temperature. The magnet approach is widely recommended for beginners, but it won't let you get the maximum performance out of the steel in many cases. The reason is that most steels require some "soaking time" at the optimal hardening temperature. The maximum amount of carbon that can be dissolved into iron is right around .8 percent. With steels that have more than or less than .8 percent carbon, you need to apply more heat and more time to get all of the carbon into solution. For example, 5160 requires some soaking because the amount of carbon, which is .6 percent, is on the low side for a good blade. You need to get all of that carbon into solution if you want the steel to reach full hardness. In a steel like O1, which has around 1 percent carbon plus some alloying elements like chromium, the soak is required to allow the carbon to free itself from clusters of carbon and chromium atoms.

The steel we're considering, 1084, has just about the perfect amount of carbon in it. So it requires the lowest heats and shortest soak times of any steel. I recommend beginners start with 1080 (more readily available), as it will give you good results with primitive equipment.

Another clue you can use to find the proper hardening temperature is decalescense. If you watch carefully as the blade nears the correct temperature, you can see the steel transforming to austenite. Black shadows flicker and pulse rapidly over the surface of the steel. This takes some practice and a dark environment to see, but it's amazing to watch. When the flickering stops the transformation to austenite is complete.

As the blade comes up to temperature, I mentally rehearse the quenching process to make sure that I'm not going to drop the blade or trip over something while I'm transferring it to the quenching tank. After it reaches 1450 F, I allow the blade to soak for about three or four minutes. This is longer than is probably necessary, but it doesn't hurt anything.

The biggest pitfall you want to avoid during the hardening heat is overheating the steel. As the steel overshoots the hardening temperature, the austenite grains start to merge, creating bigger grains. Bigger grains make the steel more brittle—bad bad bad. Overheating by 100 degrees is enough to have an effect.

Once the soak is complete, it's time for the quench. This is the fun part. I grip the tang firmly with a pair of tongs, and in one smooth motion, I pull the blade out of the forge and immerse it, point first, into the oil. With my preheated Parks #50, there's very little fuss—a few puffs of smoke, some bubbling on the surface of the oil. It's important to agitate the blade in the oil, which accelerates the cooling. I've tried both agitating up and down and back and forth, and neither causes any warping. Agitation is has been recommended by industrial heat-treaters for decades, and those guys know their steel.

What happens during the quench? The goal of the quench is to cool the steel fast enough to transform all of the austenite into a structure called martensite. If steel cools slowly, the dissolved carbon will collect together, leaving pockets of plain iron. But if it cools quickly, the carbon gets trapped in the iron, forming martensite. Martensite is the hardest, most brittle form of steel.

The quench, therefore, needs to cool the steel quickly and evenly, but not too quickly. (If you use a quenchant that's too fast for a particular type of steel, it'll stress the steel and cause it to crack.) You'll hear bladesmiths talking about missing the "nose." This is a reference to a type of graph called a isothermal transformation diagram, which shows the different structures steel forms as it cools. To simplify, you need to get the steel down below a specific temperature quickly, and then the cooling speed becomes less critical. On 1084, for example, the steel needs to go from 1450 F to around 800 F in just under 1 second. After that, you have as much as 30 to 60 seconds to get it down to room temperature.

That's the reason that I preheat the oil; warm oil is thinner and moves more freely, pulling the heat away from the blade more quickly.

If you do all these steps correctly, the chances of the blade cracking or warping are minimal. My personal opinion is that cracked blades are usually a result of using poor quality steel, failing to normalize, or overheating during the hardening heat.

Once the blade has cooled enough that I can touch it with my bare hands, I take it out of the oil and set it on the newspaper and allow it to cool to room temperature. At this point the blade should be 100 percent martensite, and it is loaded with internal stresses caused by the rapid cooling. One good visual clue is to look at the surface of the steel. As the blade heats up in the forge, black scale forms on the steel. If you get the hardening temperatures and quench just right, the scale gets blasted off the blade, leaving an otherworldly, ghostly gray-white finish on the blade.

The blade is probably between 65 and 67 on the Rockwell C hardness scale—crazy hard. If you dropped it on concrete, it would shatter like glass.

Tempering

This is where tempering comes in. By heating the blade again, you allow the martensite to soften slightly and you relieve some of the internal stresses. You're sacrificing some hardness to gain resilience. This is a good tradeoff for a razor, because 65 HRC is virtually impossible to hone anyway.

After the blade has cooled and I've wiped off any excess oil, I take it over to my grinder and do a couple of passes on the contact wheel, cleaning the forge scale off the surface and leaving the hollows bright and clean.

It's a good idea to test the hardness of the steel before you go on to tempering. The easiest—and least accurate—way to do this is to try to file the blade with a good file. Files are hardened to around 65 Rockwell C, and by observing how the file interacts with the steel, you can gauge whether it hardened or not. A file won't dig into a hardened blade—it will slide off the surface as if the blade were glass. The sound it makes is a good indication, too. A hardened blade makes a high-pitched, brittle sound. (The file may take off some scale, which is soft, but once it gets down to clean metal is should barely even scratch it.)

My tempering oven right now is a small toaster oven. These things vary in accuracy, so I got an oven thermometer to confirm the temperature. You could also use a kitchen oven.

To temper the blade, you heat it to a prescribed temperature and hold it there for two or three hours. The tempering range of steel starts around 350 degrees F and goes up to 600 or 700 degrees. Around 350 F, the martensite starts to transform into tempered martensite, which is slightly softer and much tougher than untempered martensite. The higher the tempering temperature, the softer the steel will get.

For razors, I usually temper at 400 to 425 degrees F for two hours. I've experimented with tempering blades at 350 F, and the steel is usually too hard to hone easily. On one O1 blade that I made and tempered at 350 F I spent more than five hours trying to get it honed. I eventually gave up and gave it another tempering cycle at a higher heat, and after that it honed right up.

Antique razors seem to be between 58 and 62 Rockwell C, and several of the modern custom makers shoot for a hardness of 62 to 64. I've actually made a couple of blades that were pretty soft, maybe 52 to 54, and they still shaved well. The actual number doesn't matter much, in my opinion, unless you're looking to produce and sell blades and want to be able to make specific hardness claims. There is a wide range of "acceptable" hardness levels—the blade will still shave nicely, although edge holding and ease of honing will vary.

As the blade tempers in the oven, the bright, shiny parts that I cleaned up will start to discolor again. This is oxidation forming on the surface of the steel. These tempering colors are a good indication of what's going on inside the steel. The first color to appear is a faint bronze tint. The bronze darkens to brownish, then it starts to go iridescent reddish purple, followed by blue, then finally gray. For blades, you want to temper in the medium bronze range. The exact colors vary by the type of steel, so you'll need to experiment. I usually go by the temperature, and the tempering colors just provide a nice secondary reference.

After the temper, the blade is ready for finish grinding. It's important to keep the steel from getting too hot—anything over 300 or 350 degrees will start to soften the blade again. By letting the blade get too hot, you're doing further tempering. That's why the blade will go blue if you let it get too hot. Those are temper colors. The best way to prevent overheating the steel is to grind without gloves on and dip the blade in a bucket of water every couple of passes. You will cook your skin long before the steel gets hot enough to affect the hardness.

So that's it. You can do a good heat-treatment with simple tools and some basic knowledge. Improving your knowledge will allow you to get better results with the tools you have. Better tools give you more control over the process, but you have to have the knowledge to put them to use.