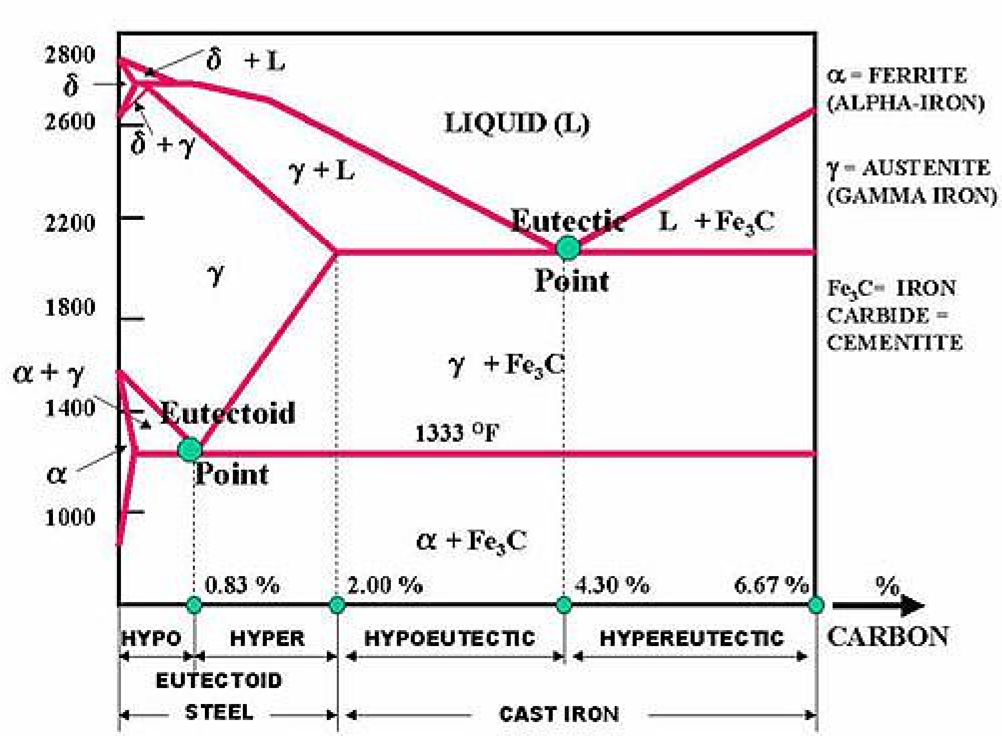
Heat Treating 101 - Steve Bloom, IronFlower Forge

This subject often feels like the proverbial can of worms. Well, it is but don't let the terminology throw you. Steel is simply iron with some carbon - if no carbon, then it's iron. First, let's look at the phase diagram. It relates the amount of carbon and temperature. Take a look at the "Liquid (L)" area (the zone from the top of the diagram down to the first red line). It tells you that very low carbon steels melt around 2800 °F. If the carbon content is 4.3%, then it melts at ~2100 °F. As the carbon content gets even higher, the melt temperature starts up again. Now look at the zones labeled "γ and L" or "L + Fe_3C". Those area are a mixture of liquid and something else. OK, then maybe (mumble, weasel, weasel), we ought to call steel with 2% or more "castable steel" because it has a lower melt temperature. Of course, we don't - it's called "cast iron" even though it is a steel. This is why you can't let the terms throw you - they often are arbitrary. For our purposes, ignore every thing to the right of 2% and below the 2nd red line from the top (because we don't deal with liquid steel unless we really foul up).

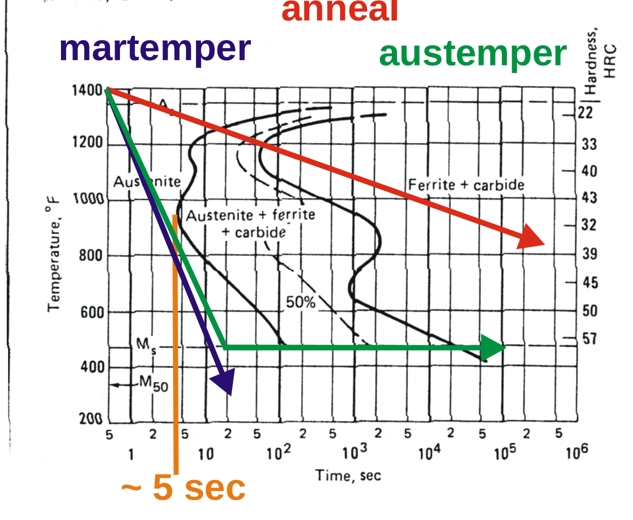


Iron-Cementite Phase Diagram

For a knife maker, all we are really doing is manipulating the solid phase crystalline structure of the steel we are using. Crystals in steel can be seen at 100x to 500x magnification after a thin section is made with a high polish and a bit of nitric acid etch. Guess why we talk a lot about grain but don't show it off. For our purposes, there are two basic crystal lattices - body-centered cubic (=bcc) and face-centered cubic (=fcc). Think **B**urr for bbc and **F**ire for ffc, i.e., bbc occurs in steel when it is cold and ffc when it is hot-really hot.

Find the area with the γ in the center - that's ***austenite***. Start at far left and about 1550 °F. The red line runs down to a green dot labeled as the "Eutectoid Point", it then zooms up to the inflection point at 2% x 2100 °F. Since tool steels usually run between 0.6% to 1.2%, all we are really concerned about is from the "E" to the "c" in Eutectoid". When we run the temperature on a given steel to the "critical" temperature, all we are doing is running it above that red line - the exact temperature needed being a function of the carbon content. When the crystal structure is in the austenitic phase, the crystals change shape and carbon is free to move. It takes energy to change the shape (just like changing ice at 0 °F to water at 0°F - 540 cal/gm, in fact), so there is a point at which pumping more energy in results in no change in temperature - the energy is being used to shape change.

The correct terms for this change is allotropic transformation (that and $4 at Starbucks...). When this all starts, the magnetic properties change too - which is why a magnet no longer sticking is a reasonable indicator of the critical temperature. The temperature corresponding to the loss of magnetism is called the "Curie Point" (yeah - that Curie) and is about 50 °F cooler than the actual critical temperature. Obviously, there is some time needed for the shape change to happen and there is time needed for the heat to get to the center of the piece - it doesn't happen instantly. In addition, if there is differences in carbon content (like in pattern-welded steel), more time is needed to allow the carbon to migrate from high to low carbon areas to create a homogeneous percentage. All of that is referred to as "soak" time.

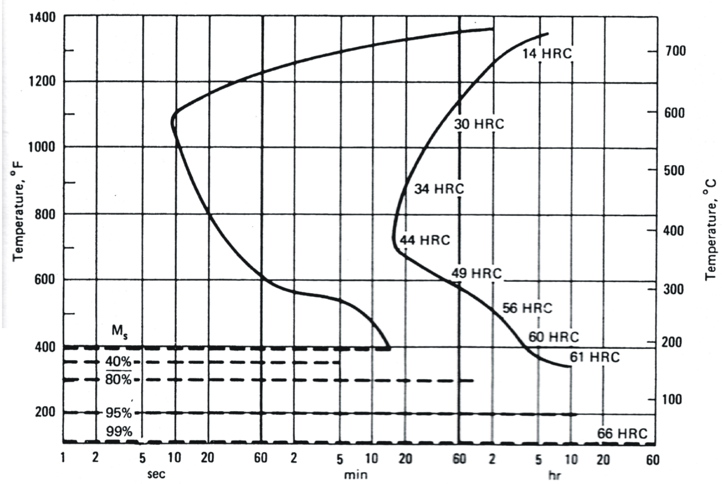


5160: Isothermal Transformation Diagram. Composition: 0.61 C, 0.94 Mn, 0.88 Cr. Austenitized at 1550 °F (845 °C). Grain size: 7. (Source: *Atlas of Isothermal Transformation and Cooling Transformation Diagrams*, American Society for Metals, 1977)

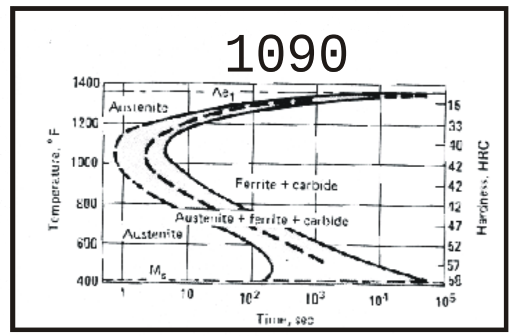
So, we now have our steel shifted over to austenite. It is kind of hard using a blade at 1550 °F, so we will have to cool it somehow down to what we can handle (and/or apply a handle). Depending on exactly how we do the cooling will control the crystal structure that results and the structure dictates the physical properties of the material. Every steel has a unique relationship of these structures depending on the exact alloy in play - that's why there are big books with all of this laid out. Let's take a look at the "Isothermal Transformation Diagram" of 5160 steel (usually just called a TTT curve - ***time-temperature transformation*** curve or an 'S' diagram -an older term). It is basically a road map. If you follow the red line, dropping the temperature from austenitic to room temperature over 10^6 seconds (11+ days), you get ***ferrite*** and maybe iron carbides (also called ***cementite***-just what you needed, another term!). Actually, all it takes is 10^4 seconds (~3 hours) to get you down near the head of the green arrow. This is *annealing* - a slow cool from austenitic temperatures. Carbides are 6.7% carbon, are effectively diamonds (=HARD), and form when there is an excess of carbon. Ferrite is simply bbc material (remember-**B**urr=cold=***b***bc) The result is soft steel due to having a crystal structure called ***pearlite*** (a layered arrangement of ferrite & carbides). It is called that because is reminded someone of mother of pearl when viewed under a microscope. This is why the "run it up to orange, toss it in some ash, go get lunch" works to make steel soft.

Now, let's follow the purple line. It starts at austenite and drops across the "M" lines without touching the left most black wavy line. If your steel follows this path, you somehow have to get the temperature from 1440+ °F down to 400 °F in no more than 12 seconds total but you have actually only 5 seconds to miss the "nose". The crystal type that forms when you treat steel like this is ***martensite*** - and it is the hardest crystal type but it is also extremely brittle. The "M" lines are also called (tada!) the "*martensite star*t" and "*martensite end*" lines, i.e., it starts forming about 475 °F and stops around 400 °F. The process is called "martempering" or more properly "marquenching". This path way is the usual liquid quench process - either water or brine for steels in which you may have 0.5 seconds to miss the "nose" or oil (for modern steels with 5 to 10 seconds to miss the "nose"). Or you may be dealing with "air hardening" steels in which a cool breeze is all that is needed. If your path way cuts across the "nose", then you get a mixture of martensite & pearlite - softer than it could have been. Typically, smiths making high-carbon blades use oil-hardening steels. In fact, the reason for developing modern tool steels was to generate enough delay so the steel would not be subjected to the high levels of stress involved in a water quench. But we are not quite done yet. Something has to be done to trade the hard for tough in martensite. That is what tempering does. There are known relationships for all steels that link the tempering temperature to the eventual final hardness and we'll take a look at one of those graphs in a second.

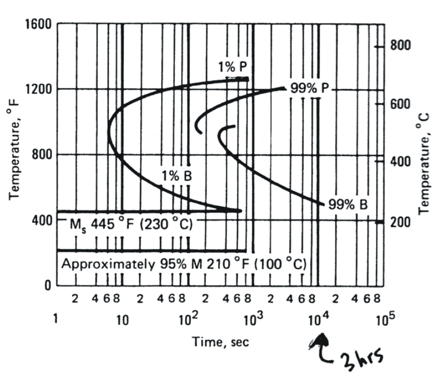
There is a remaining line on the plot - the green one (=austempering or ausquenching). If you can ram the temperature down fast enough to miss the nose, yet keep the steel at 475 °F for a couple of hours, you get ***bainite*** -- something as hard as tempered martensite and a bit tougher. This is what the salt baths are all about.



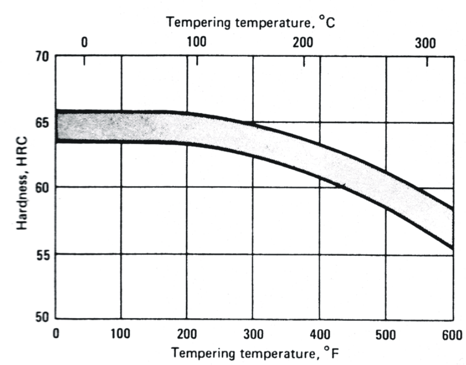
O1: Isothermal Transformation Diagram. Composition: 0.85 C, 1.18 Mn, 0.26 Si, 0.50 Cr, 0.44 W. Critical temperature (Ac_1): 1370 °F (745 °C). Prior condition: annealed. (Source: *Tool Steels*, American Society for Metals, 1980)

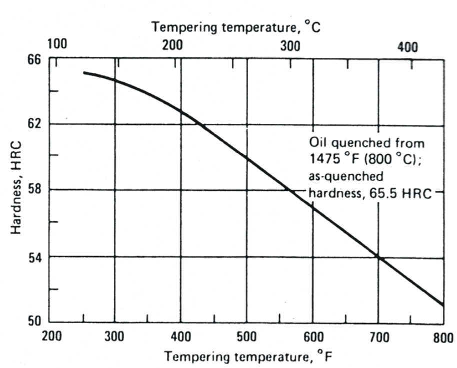


O1: Isothermal Transformation Diagram. Swedish grade showing percent pearlite and bainite as a function of time and transformation temperature. (Source: Uddeholm Steels)



O1: Hardness Versus Tempering Temperature. Austenitized at 1450 to 1500 °F (790 to 815 °C). Band approximately 2 HRC points wide. (Source: *Metals Handbook*, 8th ed., Vol 2, American Society for Metals, 1964)





O1: Hardness Versus Tempering Temperature. Austenitized at 1475 °F (800 °C). (Source: Universal-Cyclops)

O1

Chemical Composition. AISI: Nominal. 0.90 C, 1.00 Mn, 0.50 Cr, 0.50 W. **UNS:** 0.85 to 1.00 C, 0.40 to 0.60 Cr, 1.00 to 1.40 Mn, 0.030 P max, 0.030 S max, 0.050 Si max, 0.30 V max, 0.040 to 0.60 W

Similar Steels (U.S. and/or Foreign). UNS T31501; ASTM A681 (O-1); FED QQ-T-570 (O-1); SAE J437 (O1), J438 (O1); (W. Ger.) DIN 1.2510; (U.K.) B.S. BO1

Characteristics. High dimensional stability during heat treating. Relatively shallow hardening. High resistance to decarburization. Very high safety in hardening

Forging. Start forging at 1800 to 1950 °F (980 to 1065 °C). Do not forge below 1550 °F (845 °C)

Recommended Heat Treating Practice

Normalizing. Heat to 1600 °F (870 °C). Holding time, after uniform through heating, varies from about 15 min for small sections to about 1 hr for large sections. Work is cooled from temperature in still air

Annealing. Heat to 1400 to 1450 °F (760 to 790 °C). Use lower temperature for small sections and higher temperature for large sections. Holding time is about 1 to 4 hr. Use shorter time for light sections and small furnace charges, and longer time for heavy sections and large charges. For pack annealing, hold for 1 hr per inch of cross section. Cool at a maximum rate of 40 °F (22 °C) per hour. The maximum rate is not critical after cooling to below 1000 °F (540 °C). Typical annealed hardness, 183 to 212 HB

Cycle Annealing. Heat to 1350 °F (730 °C), hold for 4 hr. Heat to 1440 °F (780 °C), hold for 2 hr. Cool to 1275 °F (690 °C), hold for 6 hr. Air cool

Stress Relieving. Optional. Heat to 1200 to 1250 °F (620 to 650 °C) for 1 hr per inch of cross section (minimum 1 hr) Cool in air

Hardening. Heat slowly. Preheat at 1200 °F (650 °C). Austenitize at 1450 to 1500 °F (790 to 815 °C) for 10 to 30 min, then quench in oil. Quenched hardness, 63 to 65 HRC

Stabilizing. Optional. For intricate shapes, stress relieve temper at 300 to 320 °F (150 to 160 °C) for 20 to 30 min. Refrigerate at −150 to −320 °F (−100 to −195 °C). Temper immediately after part reaches room temperature

Tempering. Temper at 350 to 500 °F (175 to 260 °C) for a corresponding approximate tempered hardness of 62 to 57 HRC

Recommended Processing Sequence

- Normalize
- Rough machine
- Stress relieve (optional)
- Finish machine
- Preheat
- Austenitize
- Quench
- Stabilize (optional)
- Temper
- Final grind to size

Now, let's take a look at O1. First compare the "nose" gap for O1 (~9 sec.) versus the gap for 1090 (the diagram on the upper right) (< 1 sec.). Just another example of why modern steels exist. Take a look at the left-middle plot. It shows how to get bainite but more importantly, compare the two 'S' diagrams - similar but definitely different, i.e., gaps of 9 versus 6 seconds. One aspect that knife makers deal with is what are small differences within the accepted limits of composition for a given steel can make big differences in the heat treat. This is why you really have to test what you are making. Finally, take a look at the remaining two plots. They tell you what temperature to cook the steel to get a given hardness, i.e., you can move from 66 Rockwell C to 58 by cooking at 550 °F. If you know what hardness you want, you know how to get it.

The books also contain information like that shown above - specifically composition and guidance on heat treating. By now you recognize that normalization, annealing & hardening require reaching the critical temperature but those are listed as 1600, 1450 & 1500 °F respectively. Which is "right"? Well, if you remember what was said about grain size, when you normalize, a little overshoot means everything gets affected. When you anneal, the goal is softness and grain isn't as important, so undershooting is okay. When hardening, on the other hand, grain size is critical, so you don't want to be running too hot and mucking up the grain size you got from the normalization. In practice, take an average - say 1550 °F -- and you will be OK.

Look under "Hardening" above - it recommends a soak time for 10 to 30 minutes at 1500 °F. The industrial standard is the 1" diameter bar, i.e., it takes maybe 30 minutes to get to the center and do the magic. So, if it's 30 minutes to penetrate 0.5" (to the center), and our blade is maximally 3/16" thick, or 0.09375" to the center , then the blade is about 18% of the distance to center relative to the standard bar. This means that the soak time range drops from 10 to 30 minutes to 1.8 to 5.6 minutes. But a knife actually has a thinner edge than the spine (check out the dimensions listed for the completed rough forge) - something like 0.045”. The soak time is now 0.2 to 0.6 minutes - not 30 minutes! I have heard experienced makers cite the book times as the times they soak their steel - maybe they don’t know about the 1” rod factor. There are steels (primarily stainless) that do require long soak times because of the amount of chromium involved. These steel also can have “retained austenite”, i.e., on quench, some to the crystal structure fails to convert to martensite. By dunking these steels in liquid nitrogen (cryo-quench), the remaining austenite can be flipped over to martensite and the steel attains a more uniform and greater hardness. For most high-carbon, non-stainless steels, retained austenite is not a problem and cryo-quenching is not really needed (unless as a way to charge more and impress the customer).

There is really only one more aspect that ought to be discussed. Just what is that “Eutectoid Point”? It wasn’t added to the plot just to mark the 0.6 to 1.2% C austenite boundary. I like to think of that point as the Oreo cookie-milk point, i.e., the point at which the milk and the cookies run out together. If you have just the right carbon content (0.77%), there will be 100% martensite formed when quenched - which gives the resulting steel maximum hardness. Remember, on slow cooling, you get a mixture of ferrite and carbides (mostly soft, with some hard bits) that simultaneously form when the steel has 0.77% carbon. However, we are talking about fast cooling here, so we get 100% martensite. This type of steel is called a “Eutectoid” steel. If there is less than 0.77% carbon (=hypoeutectoid), then the carbon gets sucked up into martensite but there isn’t enough to go around, so some ferrite is formed and carbides don’t appear. The overall effect is a steel that is a bit softer than an eutectoid steel. If there is excess carbon, i.e., more than 0.77% (=hypereutectoid), then a mixture of martensite and carbides form - making a hard steel with some VERY hard bits - hell on stones and files. Sooo ... how soft can steel be to make a reasonable cutting tool? The usual estimate is 0.6% as the lower limit and Japanese smiths seemed to have agreed on 0.63% for their weapons. If you are hand finishing, you definitely do not want carbides, so running a bit low makes sense. If you have a grinder, then carbides are not a problem and you can use a hypereutectoid steel (like O1). The carbides enhance edge retention, so that’s good. We temper our blades to trade off hardness for toughness and rely on the carbides to take up the slack. The Japanese typically left their blades at the as-quenched hardness (60+ Rockwell C) to provide a good edge and expected that the combination of a soft-core, pattern-welding, differential quenching, and user ability would handle the toughness side of things.

If you look carefully at the first diagram, it isn’t totally in synch with what I’ve just said. That’s just another example of why this can get confusing, so remember the big picture and don’t sweat the tiny details. The bible for all of this is Unterweiser,P.M., H.E.Boyer & J.J.Kubbs. (1982) “Heat Treater’s Guide: Standard Practices and Procedures for Steel”; Amer.Soc. for Metals, Metals Park, Ohio. The book is on the size range of a big city telephone book and typically costs $300+ (though I’ve seen them used for about $100). Most of it is stuff like the O1 information for a mind-boggling number of steels you never heard of and will never use. I just went to the library with a pocket of quarters and copied the relevant sections.

By now, you are thinking “I just want to bake a cake - not get a graduate course in yeast biology and organic chemistry”. You’re right but a little knowledge is always good. For the usual knife maker, you simply have to

:(1) Get the steel up to critical temperature;
--- then either---
(2A) Anneal by tossing it into a container with wood ash or vermiculite for a couple of hours; or
(2B) Quench it in something that drops the temperature fast enough to miss the “nose” and doesn’t burn your shop down and temper in a used toaster oven at the target temperature for the eventual hardness needed (usually 375-400 ^{o}F for skinners to 450 ^{o}F for bowies and other big blades).

So, let’s take a look at these procedures.

Getting steel up to critical temperature is relatively easy. Toss it into a forge, tap it with a magnet once it starts to turn orange, and move onto the quench once the magnet doesn’t stick. This works but it is hardly optimal.

We first have to talk about scale. As the steel passes about 1200 ^{o}F, the oxygen in the atmosphere starts to react to the iron on the surface of the blade to form ferric oxide (precisely Fe_3O_4). The more scale, the more cleanup after the heat treat. So - scale is BAD because it means more grinding and more grinding means a greater opportunity to overheat the steel and compromise the heat treat. The solution is obvious - keep the oxygen from reaching the steel. Some folks use electric ovens with argon atmospheres (which, incidentally, tends to kill the heating elements in short order). Others use hot-salt baths (like me). Others coat the blade with some form of heat-resistant material, like satinite. Others just grind more and use the dunk tank a lot. We’ll try the satinite approach.

Now we can discuss even heating. If a blade has cold and hot areas, some of it may be too hot and other parts too cold. On quench, warping is likely. So we want even heating. In a typical coal or charcoal forge, tossing a heavy wall pipe onto the forge and using the pipe as an oven helps to even out the heat but it is hardy optimal. Using an electric oven (like a Paragon) is better but it isn’t easy to make sure that the steel is really at the temperature of the oven’s thermometer. When you pop the door open to do the magnet test, the temperature drops and there may be a long wait (like 15 minutes or more) before the oven gets back up to critical. Meanwhile, scale is forming if the steel is exposed to oxygen. Salt baths shine here - no oxygen, even temperatures, and excess heat capacity (lots of salt, small amount of steel equals stable temperatures).

Next we have to talk about grain. As mentioned when discussing normalization and heat-cycling (back in the forging document), grain grows as temperature exceed the critical temperature. There is no good way to bank a coal or charcoal forge down to provide just the right amount of heat. Gas forges are better but typically the burners create hot & cold spots with the hot spots way over critical. Here again, salt baths excel.

The downside to salt baths is that they are a pain and an expense to run. They eat shop time. It takes about an hour from light off to reach 1550 ^{o}F and about that amount of time to get back to a storage mode. They are great if you are doing 20 to 30 blades. Not so much for a single blade. So what are we going to do?

We are going to use the “Don Fogg Sword Austenizer” - a 55 gallon drum with a single gas burner. The combination of a small burner, a large volume, and a diffuser plate results in a highly controlled temperature chamber. After the coarse grind, we will coat the blades with satinite to reduce scale and hang them in the drum. After a few minutes, the blades will be at critical and we can pull them out to air cool to below 1000 ^{o}F. We’ll repeat this three times and then evaluate how well the satinite is working. If necessary, we can do a quick scale removing grind, recoat with satinite, and put them back in the drum. If the surface looks acceptable, they will just go back in for the final heat.

Eventually, we will oil quench the blades in Brownell’s “Tough Quench” - a commercial quenching oil. We could use any reasonable oil with an acceptable flash point (peanut, olive, soy, etc.) or even Goodard’s Goop (40% lard, 40% ATF or hydraulic oil and 20% paraffin). All of these can ignite, so due caution and snuff lids will be used. The blades get tossed in the toaster oven at 400 ^{o}F for an hour to temper and you can get back to the grinders.

