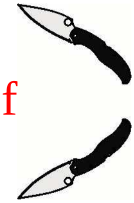
Steel Metallurgy in Brief



(*I am indebted to Professor John D. Verhoeven, whose book* Steel Metallurgy for the Non-Metallurgist *served as a valuable aid to me in writing this chapter. I would also like to thank James Beckman, President of Crucible Industries® for taking the time to consult with me on the subject of steel metallurgy*.)

My goals in this chapter are to discuss the following concepts:

1) The *properties* of steel that are relevant to knife blades, namely, toughness, hardness, edge retention, wear resistance and corrosion resistance.
2) The basic *processes* that a steel undergoes in an attempt to make it excel in one or more of these properties. This includes the addition of alloys like tungsten, molybdenum or vanadium to the steel and the subsequent *heat treatment* process.
3) What actually happens to the steel during these processes. This will give you some insight as to why the number of possible steels is essentially unlimited and why it is probably impossible to optimize *all* of the aforementioned properties of knife steel at the same time.

In order to accomplish these goals, I will need to briefly discuss the structure of steel and how that structure changes when the steel is heated and cooled in various ways.

As you will see, during the processing of a particular steel, a few degrees of temperature more or less, a few minutes at a given temperature more or less, a few percentage points (by weight) of an alloy such as manganese more or less can make a *significant* difference in the performance of a knife blade.

The Properties of Steel

Even before discussing what steel is, it is important to understand which properties of steel are important in making a good knife blade. Generally speaking, there are several bad things that can happen to a knife blade during use. A blade can

1) crack or chip,
2) wear down, that is *abrade*,
3) bend, that is *deform*,
4) corrode, that is rust or become discolored.

Let us examine these properties in more detail.

Toughness

Toughness is the ability of the steel to resist chipping or cracking or the ability to flex without breaking. It is the opposite of **brittleness**. Common toughness tests include **impact tests**, such as striking the cutting edge (apex) of the blade with a steel rod (cringe!) and **bend fracture tests**, such as measuring the angle through which a knife blade will bend before it snaps.

It is interesting to note that most knife steels are **notch-sensitive**, which means that the presence of a small notch in the steel will make the blade far more sensitive to fracturing near the notch.

Hardness

Hardness is the ability to resist *deformation*. Rather than smashing the edge of a blade with a steel rod to see if the blade will chip, we could *push* the blade's cutting edge into a steel rod to see when and by how much the edge deforms. This is a measure of hardness. (Hardness should not be confused with *hardenability*, a property that I will discuss later.)

Hardness is often measured for knife blades on the **Rockwell C-scale**, abbreviated **HRC**. The steel in folding knives usually falls somewhere in the range of about 58–64 HRC, but most fall in the range 60–62 HRC. Generally speaking, the harder the steel, the less the edge will wear and the better it will retain its edge, but the more brittle it becomes, causing it to be more likely to chip or break. Life is full of tradeoffs! I will discuss other measures of hardness a bit later.

Wear Resistance

Wear resistance is the ability of the steel to withstand *abrasion* due to the friction that the blade encounters when it is used to cut abrasive material such as cardboard, wood or rope. It is also the ability to resist the *adhesion* of foreign particles to the blade. Generally speaking, for a given steel, the harder it is, the more wear resistant it is.

Edge Retention

A somewhat more imprecise property is **edge retention**, which refers to how long a blade will remain sharp (whatever that means) with use. This property is rather difficult to measure quantitatively, but it would seem to be a consequence of the blade's hardness, toughness and wear resistance all put together.

Corrosion Resistance

Corrosion resistance is the ability of a steel to withstand corrosion (oxidation) from moisture, humidity and salt.

Hardness Tests

I think it is useful to discuss some of the different ways in which hardness is measured and to give some specific hardness values for later comparison.

We will see that modern steels contain certain carbon compounds called **carbides**, that is, chemical compounds of carbon and metal. Common examples are tungsten carbide, molybdenum carbide and vanadium carbide. Carbides are much harder than plain steel (iron and carbon) and their presence gives the **alloy steel** used in knife blades its characteristic hardness. Specific hardness values can give us a quantitative idea of the hardness of various carbides. For instance, we will see that vanadium carbide is much harder than either molybdenum carbide or tungsten carbide.

Another reason for looking at specific hardness values is to compare the hardness of sharpening abrasives with the hardness of the steel that they are intended to abrade. For example, two common abrasives are silicon carbide and aluminum oxide. As it happens, silicon carbide is harder than aluminum oxide and so makes a more aggressive sharpening medium. This explains why silicon carbide is used more often in the coarser sharpening stones.

There are many different tests of hardness, with names such as Rockwell A–H, K, N and T, Vickers, Knoop, Mohs, Brinell and Leeb. Each of these tests is appropriate for specific types and shapes of material. For example, some tests are specifically designed for thin materials or for brittle materials or for steels or for ceramics.

Although various charts are available to convert one hardness measure to another, since the tests are designed for different purposes, one has to be a bit skeptical about the accuracy of these conversions. In any case, it seems somewhat difficult to compare the hardness of different types of materials unless the materials have been tested by the same method.

Most tests use an **indenter** of a specific shape (for example, a cone, a pyramid or a ball) and composition (for example, diamond or steel) to make an indentation in the material that is being tested. Then some sort of geometric measurement is taken of the resulting indentation to get a numerical value, which is then transformed by a mathematical formula into a hardness measurement.

Hardness measurements must always be taken with a grain of salt. For example, knife blades should really be tested at several different points, not just at one point. Also, hardness tests only reveal the *surface* hardness of a material and not its internal hardness, which may be significantly different.

The Rockwell C-Test for Hardness

As I mentioned earlier, knife blade hardness is generally measured on the **Rockwell C-scale**, abbreviated **HRC**. This test is performed by first applying a **minor load** (penetrating force) to the material to be tested. Then the load is increased by an amount called the **major load**. Finally, the major load is removed, but the minor load is maintained. The “C" in C-test refers to using a 120° diamond cone as the indenter to apply the loads.

The depth of penetration of the major load is measured on a dial. Penetration depth and hardness are inversely proportional and so less penetration (that is, a harder steel) gives a higher number on the Rockwell C-scale.

Actually, each type of knife steel has a recommended hardness *range* within which the steel performs best. For example, for CPM-S30V®, the range is 58-60 and for CPM-M4 the range is 62-64. However, the hardness of the steel of a *particular* knife is determined by the manufacturer during the heat treatment process for that knife (and is presumably within the steel's most effective hardness range). I will describe the heat treatment process a bit later.

The Knoop Test for Hardness

The **Knoop hardness test** is a test used for very brittle or very thin materials, where only small indentations can be permitted. In this test, a pyramidal-shaped diamond is pressed into the material and the indentation is examined under a microscope.

Figure 60 gives some Knoop values. I have also included a few Rockwell C-test values.

Material	**Knoop Hardness**	**HRC**
Talc	20	
Silver	60	
Copper	163	
Annealed steel	200	
Pearlite	438	
Glass	530	
Martensite	800	
Quartz	820	
Hardened steel	650–846	56–65
Iron carbide (cementite)	1025	
Chromium carbide	1725	66–68
Molybdenum carbide	1800	72–77
Tungsten carbide	1880	72–77
Aluminum oxide	2100	
Titanium carbide	2470	
Silicon carbide	2480	
Vanadium carbide	2660	82–84
Boron carbide	2750	
Titanium diboride	4400	
Diamond	7000	

Figure 60: Some Knoop/Rockwell hardness values

The Mohs Scale

The **Mohs scale** of hardness is a test that characterizes the **scratch resistance** of one material with respect to another material. Specifically, the Mohs value for a material is determined by what it can scratch and what can scratch it. For example, if a certain material can scratch glass (Mohs 5.5) but is scratched by titanium (Mohs 6), then that material has a Mohs value somewhere between 5.5 and 6. This test is useful in understanding the effectiveness of certain sharpening media (like ceramic or diamond).

Figure 61 shows some typical Mohs values. Unlike the other tests, this test is *qualitative*, not quantitative. That is, the actual Mohs numbers mean *nothing* by themselves but are only meaningful when we compare two Mohs values. For example, a Mohs value of 3 means *only* that material with a higher Mohs values will scratch that material. It would be *incorrect* to say that titanium (Mohs 6), for example, is twice as hard as gold (Mohs 3).

Mohs	Material
1	Talc
2	Calcium
2.5–3	Gold, Silver
3.5	Platinum
4	Nickel, Iron
4–4.5	Steel
5.5	Molybdenum, Glass
6	Titanium, Manganese, Niobium, Rhodium, Silicon, Iron carbide
7	Quartz, Vanadium
8.5	Chromium
9	Aluminum oxide
9.3	Silicon carbide
9–9.5	Tungsten carbide, Vanadium carbide, Titanium carbide
9.5–10	Boron carbide, Boron nitride
10	Diamond

Figure 61: Some Mohs values

Heat Treating Improves Hardness

To improve hardness, steel undergoes a process called **heat treating**. Here is the heat treating process in brief. I will explain these steps in more detail later.

Preheating

Preheating is the process of heating steel to a certain temperature and holding it at that temperature until all parts of the steel are in thermal equilibrium. Preheating relieves internal stress within the steel and reduces the risk of cracking.

Austenitizing

Austenitizing refers to the process of heating the steel to a very high temperature to change its crystal structure. As we will see, this permits the iron in the steel to absorb more carbon, allowing the final result to be harder and more wear resistant.

Quenching

Quenching refers to the *rapid* cooling of the steel in water or oil to actually harden the steel. However, quenching does make the steel very brittle. In fact, some quenched steel is so brittle that it cracks spontaneously at room temperature!

Tempering

Tempering refers to heating the steel and then cooling it in air in order to toughen the quenched steel. The temperature and length of time used in tempering can significantly effect the final outcome of the steel. Tempering trades some hardness for toughness.

As you can see, several steps are required in heat treating and there is a tradeoff between hardness and toughness. Nevertheless, heat treating basically amounts to repeated heating and cooling of the steel to different degrees and for different periods of time. Note that there are two parameters to each step of this heating/cooling process: *temperature* and *time*. Varying either one of these parameters can have *profound* consequences to the final product, which is why

> *the quality of the heat treatment process has a great deal to do with the final quality of a knife blade.*

The Composition of Steel

Iron alone will not make a good knife steel, for it is too soft and too weak. However, adding carbon to steel in very small quantities (say between 0.7% and 3.0% by weight) produces a mixture that is much harder and much tougher than simple iron. This is accomplished through the heat treating process. However, as always, there is a tradeoff. The higher the concentration of carbon, the more brittle the steel becomes.

Types of Steel

Steel can be classified into several groups as follows.

Pure Carbon Steel

I will use the term **pure carbon steel** to refer to a compound composed solely of iron and carbon. It generally does not exist in real-world environments but it will be useful for our discussion to keep things as simple as possible.

Plain Carbon Steel

Practically speaking, along with iron and carbon, most (some say all) modern steels contain small amounts of manganese, along with small amounts of impurities, such as sulfur and phosphorus. These steels are referred to as **plain carbon steels**.

Carbon Steel

Unfortunately, the term **carbon steel** means different things to different people. Some people use the term carbon steel to mean *non-stainless* steel. (I will discuss stainless steel in a moment.) In case you are interested, the *American Iron and Steel Institute (AISI)* defines carbon steel as follows:

> Steel is considered to be carbon steel when no minimum content is specified or required for chromium, cobalt, columbium [niobium],