William E. Bryson

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DEDICATION

To my dear wife Sharon, who supported me through all the years of late nights putting on the seminars that led to this book. She never complained and took it all in stride. Her proofing and suggestions for this book were invaluable.

I also owe a great deal of thanks to George P. Burgon. He always encouraged and supported my efforts. He gave me the opportunity to learn heat treatment and tool steels inside and out. Without him I could have helped no one. Thanks, George.

Contents

INTRODUCTION

Bad habits have been, or will be, developed in heat treatment procedures in most every shop all around the world. For that reason, this book will step on toes. You may feel you haven't done too badly the way you've been doing things all these years, and that you have gotten by pretty well. This book isn't meant to change everything done in a shop. It is meant to change only the things that will lengthen tool life and remove dangerous practices. It will show you the proper steps to heat treat — not the only way, but the right way! There are shortcuts that can be taken, some with little risk, some with very severe risk.

One very important industry that is not directly addressed in this book is the forging or blacksmithing industry. Today, many forgers use some very sophisticated heat treating equipment, but there is a whole array of forging shops and smithies who do heat treatment from a forge fire judging color by eye, soaking for uncontrolled lengths of time, and quenching in crankcase oil. If you're in this industry, it's important that you understand these same basics and realize what your shortcuts are doing to the finished product. All of the metals covered in this book can be forged, but all of these metals can fail if not handled properly in heat treatment. We all know that economics greatly affect the path of manufactured products. For this same economic reason you need to be aware of the basic information that will allow you to be able to understand how any shortcuts you take could affect your products.

Heat treating is indeed a science. It's an exact science. It is not a guessing game or something that should be taken lightly. Unfortunately, many company managers and company owners think that heat treating is a simple process that doesn't require the degree of expertise that some other operations require. The furnace itself is often stuck over in a dark corner and seldom maintained. All too often, it gets little consideration in the overall plan of things.

Think about this potential scenario. Picture yourself as a manager of a company that stamps an important part that is integrated into your product line. Your engineers spent days developing the product and the drawings to make the part work in your application. Then you took an order from your customer for your new product line and gave your word to deliver on an agreed schedule. You paid good money to design just the right tool, and more good money to pay well-trained toolmakers who spent days or weeks machining the parts of the die to make your part. Then, after all this careful preparation, you subject the virtual lifeblood of your company to a short little process of 2 or 3 hours in a well-used furnace, with operators who want to take pride in their vocation but were educated in heat treating from all sorts of information sources.

It might remind you of your emergency brake in your car. When you get to the point that you really need it, and if it's not been taken care of, or it's broken, then it's kind of late to think of fixing it. Or it might remind you of taking your wife's car to the auto mechanic who's never repaired an emergency brake in his life and is given only half an hour to complete the job by his supervisor's schedule.

This book came into existence after years of dealing with engineers and other people working in heat treatment. It was evident that there was a need for good, sound, information and instructions. The biggest contributors to this book were the several thousand metal users who attended over 250+ seminars conducted by the author. They provided examples of their problems and failures to be explored and solved during these seminars. In every company and every seminar, the response was one of surprise because of better techniques, of one kind or another, discovered during the seminar. Follow up of these seminars, and the dissemination of information, showed that millions of dollars have been saved by these techniques. The problem that remained after these seminars were complete was the lack of follow-up training and reliable reference materials available to new toolmakers, heat treaters, and engineers. Thus, the need to write this book. Much of it is written just as it was given in the seminars, and you will find definitions of many terms placed as they occur instead of in a glossary.

The original selection process of tool steels used in the text was developed and copyrighted by the author in 1980. In this book the selection process is newly designed into a target to draw sights on and AIM for the best. The information concerning the machinability, the shock resistance, and the wear has not been available in a single source until now. The information was gathered and interpreted from many mill sources and compared to authoritative data as published by ASM International in many of their fine books. All of it was checked, and double-checked, to provide the very best, correct, data available.

It took years to compile the personal library to put this information together.

This book was started several years ago, and the first version was completed in March of 1991. Since then, it has been revised and updated constantly to include new information. From the outset, the goal has been to write an inexpensively priced book that will be accessible to every toolmaker, machinist, and engineer working with tool steels. The information that you will find inside will pay for the cost of this book over and over again, and it is likely that your company will find that the information in these pages will result in savings of lots of time and money.

Bill Bryson
AIM (Advisor in Metals)
January, 2005

DISCLAIMER OF LIABILITY

The material presented in this book is intended for general information only and should not be used for a specific application without careful analysis and study of the intended use. Anyone using this information or relying on it assumes all risk and any liability arising from their applications and uses. Please note that all Centigrade temperatures have been derived from their Fahrenheit equivalents and rounded to the closest five degrees Centigrade.

Please also remember, this book isn't meant to change everything you've been doing in your shop. It is meant to change only the things that will lengthen tool life and to remove dangerous practices from your shop. This book will show you the proper steps to heat treat tool steel — mind you, not the only way, but the best way known today! Take some of the shortcuts if you must, but be prepared for the sacrifice that may come as a result of that choice.

PREFACE

THIS IS NOT A BOOK ABOUT METALLURGY, BUT A BOOK THAT DESCRIBES IN SIMPLE TERMS WHAT HAPPENS TO METAL DURING HEAT TREATMENT!

The purpose of *Heat Treatment, Selection, and Application of Tool Steels* is to make the art of heat treating an understandable practice, to remove the mystery that seems to surround tool steel heat treatment, and to provide a rational basis for the intelligent selection of a particular tool steel based on its intended application. It is written in clear, understandable, everyday terms and it does not cover a multitude of subjects in order to make a lot of pages. This book is aimed directly at the area of heat treatment. It deals with it head on and moves to the selection process.

There are a great many books available that attempt to deal with tool steels and heat treatment. Unfortunately, they have a tendency to get bogged down in the numerous different types of furnaces and equipment that are available throughout the world. They leave much open for guesswork on the real subject of heat treatment. This book avoids delving into equipment specifications in order to concentrate on selection, heat treating, and performance. If you need equipment, you and your company can deal with your requirements by talking to the equipment manufacturers and dealers to select a furnace that's ideally suited to your needs. If you need information on the different types of furnaces that are available, look into the other books dealing with the subject of furnaces designed for tool steel and heat treatment and contact reputable furnace manufacturers. They will give you a good understanding of the basic differences among furnaces and help you with your specific needs. Don't forget to talk to a lot of fellow heat treaters from other companies in your area. Get to know your counterparts and don't be afraid to question them in depth about the good and bad points of their equipment. And don't let them forget to talk about those bad points. Those may be the ones that will affect your needs the most.

You're going to find several chapters devoted to the heat treatment process in easy to understand, basic terms. You will also find there are a couple of areas of metallurgy, and their terms, that need to be understood sufficiently if you are going to master heat treating. But again, this book will describe those terms in everyday language in order for you to fully grasp and understand these basics without the confusion of long metallurgical terms and definitions.

Just don't give up. If you don't understand a topic, it's probably discussed in another area of the text. The book is specifically going to address the heat treatment of the tool steels that you would use every day in your tool and die shop. To really get a grasp on the subject, you need to read Chapters 1 through Chapter 5 completely. *Even if you don't use D2, it is very important that you read Chapter 5.* It is there so that you will get the foundation education for heat treating all the other grades.

Most tool rooms have their own furnace, usually an open air type, that they depend upon to harden the tools and dies used in house. Don't feel badly or ashamed about the equipment you have to use, just learn to use what you have as well as you can. The bigger concern is for the tool room that doesn't have control of the process at all.

Some of you are working, or will work, in big factories that have a centralized heat treating department that does all types of heat treating. Some of you will send your tools out to commercial heat treaters to be hardened. The needs and processes are the same in all cases. The criterion that's different is the need to understand how to do it right or how to tell someone else how to do what you want done. Centralized or commercial heat treatment is usually geared for large batches of work flowing in large quantities. Your needs, as a toolmaker of small quantity heat treatment, is usually more of a bother to these shops than what it is worth economically. But they solicit tool hardening in hopes of getting some bigger batch work from your company later on. This gives even more reason for you to be more specific in detailing your requirements when you use other sources to heat treat your tools. It is always a recommendation that the tool room should have its own equipment so you can control the outcome. After all, the tools need to wear and stand up properly or the company won't realize the profit levels it expects on those so called big batches.

During the course of this book, you're going to get a thorough understanding of how to heat treat parts without sacrificing wear, and you will learn how to minimize the loss from cracking or distortion. You invest great amounts of time and money into machining the parts. You surely don't want to lose them because of a misunderstood rule or a faulty shortcut.

This book is also going to introduce an innovative approach to tool steel selection by looking at 28 of the more popular grades of tool steel on the market, along with 3 alloy steels, and explaining the basics of how to evaluate each application. Then, and only then, can you make an educated selection. There is no single tool steel that can be used for all applications. It is hoped that the Advisor in Metals (AIM) Tool Steel Selector target, introduced and explained in Chapter 20, helps you to improve or reaffirm where you're going.

Chapter 1

What Is Steel?

Steel is made by simply adding a small percentage of carbon to iron ore. Pure iron is a soft, ductile material, but the addition of carbon changes it to a hard, strong metal. The amount of carbon added to the mixture affects how hard and how strong the metal gets, which is stated in terms of the strength and ductility of the steel. Generally, the higher the carbon content, the harder the steel is in both the annealed and hardened state. But, when the percentage of carbon added approaches or exceeds the 3% range, the metal undergoes a change from the addition of this high percentage of carbon and becomes cast iron instead of steel.

Low carbon steels are steels that have a carbon content of 0.08 to 0.25%. These are considered general machining steels and are hardened only by carburizing. Grades such as AISI 1018 or AISI 1117 are common grades of low carbon steel.

Medium carbon steels have carbon contents that range from 0.25 to 0.60%. These steels generally fit the description of medium alloy steels. These steels can be hardened as they are, but they will not develop high hardness levels as used in most tooling applications. They are generally very tough, strong steels used in applications such as gears or axles or in applications with bearing journal surfaces. Grades such as AISI 1045 or AISI 4140 are common medium carbon steels.

High carbon steels, having carbon contents that range from 0.60 to 2.40%, are considered high alloy steels and tool steels. Grades of AISI 1095 to high speed steels are within this group.

The AISI (American Iron and Steel Institute) grade identifier system for the various grades of steel indicates what the carbon level is for these low and medium carbon steels. For example:

- AISI categorizes the steels into a grade system identified in the first two digits. In an AISI 1018 grade, "10" signifies that this steel is a plain carbon nonresulfurized steel. Sulfur is typically added to steels to increase machinability. (See Table 1.1 for more information regarding the effect of elements.)
- The second set of digits in the grade identifier tell us the percentage range of carbon, stated as the nominal. That is, a grade identified as 1018 means this is a plain carbon nonresulfurized steel with nominal carbon content of 0.18%. Adding the decimal after the first two digits allows you to know the nominal carbon content of all steels in the AISI grading system.
- If there is a letter in the center of the designation, such as 12L14 or 11L17, the letter indicates an added element. To determine the carbon content, add the decimal after the alpha character.
- Here are a few other common grade prefix characters:
  "l l" indicates a resulphurized steel.
  "l2" indicates a free machining resulfurized and rephosphorized grade steel.
  "3X" (31, 32, 33 and 34) indicates nickel-chromium steel.
  "41" indicates a chromium molybdenum steel.

As stated previously, carbon effects changes in the ductility and strength of steels. The real accomplishment is the ability of being able to harden steel and make it usable for a wide variety of tools and applications.

If you were to attempt to heat treat an iron base material (ferrous metals) that only contained carbon, and the content was high enough, it would allow you to obtain a case hardening on the surface of the steel. AISI 1095 is a good example. AISI 1095 has a minor amount of manganese that adds strength, but adds nothing to the depth of hardening ability in the small amount present. Therefore, if you heat AISI 1095 to its critical temperature (heat treatment or austenizing temperature) and quench it in water or brine solution, it will produce a very hard case on the steel, but to a depth of only 0.040" to 0.080" (1.016 to 2.032 mm). The core, or center, of the steel remains unhardened and very tough.

If enough manganese were added, 1.5% for instance, hardness depth would be increased. Table 1.1 will help us see what effect elements have on steel.

Table 1.1 Effect of Elements on Steel

The Element*	The Effect
Carbon	.06 to .40% allows shallow case hardening. .40 to .60% allows easier case hardening. .60 to .80% increases hardenability. .80% up increases wear, not hardness.
Manganese	Increases deeper hardening abilities.
Silicon	Adds strength and toughness.
Chromium	Adds wear resistance and toughness.
Nickel	Adds toughness and some wear.
Tungsten	Adds wear resistance.
Vanadium	Refines grain structure.
Molybdenum	Adds heat resistance and hardenability.
Cobalt	Imparts heat resistance.
Columbium	Adds wear resistance.
Sulfur, Lead, Phosphorus, Calcium	Imparts better machinability.

*See text for notes dealing with these elements.

The elements that give better machinability — sulfur, lead, phosphorus and free carbon — are pure elements from the earth and as such should be classified as a form of dirt. In fact, when they are added to steel they make the steel dirty in the sense that they do not homogenize, or blend together, during the steelmaking process. They have a tendency to segregate and form chemical chains or groups. These groups, in their unhomogenized state, don't accept the other elements that allow hardening to take place. For this reason, they are not often used in tool steels as they can have a pronounced bad effect on tool life if they congregate near a cutting edge. On mill certification documents, you can often see minor amounts of sulfur and phosphorus reported in some tool steels — so minor, that they have no major effect on the cleanliness of the steel. The only true, free machining tool steels that are still popular are the O6 and A10 grades. These grades receive an extra amount of carbon added to the melt just prior to the pour, which turns into free graphite within the solution. This aids the machinability dramatically, but also can ruin tools due to the carbon groups that form in pockets throughout the metal. There are many instances in which the increased wear resistance in A10 is spectacular due to the super lubricity available for certain applications like draw dies and forming tools.

You will notice in Chapter 20 dealing with tool steel selection, A10 is not included in the tool steel selector. That is due to the fact A10 is a proprietary grade made primarily by only one mill. If used with discretion in light of this single sourcing, it can be a good material for a tool room to have in its arsenal. The other free machining grade, O6, is included since it is made by several domestic mills and is readily available.

Chapter 2

Exactly What Is Heat Treatment Doing?

Heat treatment is a host of things. The following description will provide a basic overview in a very simple broad-brush approach because heat treatment can be accomplished in so many different ways and mean so many different things to different people. For example, you can heat metal with a torch, an electrical induction coil, or a pot of molten salt; or you can use lead baths, fluid beds, or (the most common way) a furnace.

Here is something interesting to ponder. Heat treated tool steel is used to produce, or is a part, either major or minor, of every type of product or service in the world, with very few exceptions. This means that everything you touch, see, taste, hear, smell, or think about was manufactured or in some way has been touched by tool steel in its journey to you.

1. The material has to be heated to a certain **Temperature.**
2. The material has to be heated for a certain **Time.**
3. The controlled removal of heat in the material causes **Transformation.**

Figure 2.1 The TTT Diagram.

Metallurgists refer to Figure 2.1 as the TTT diagram. It shows the three steps required in all processes of heat treatment. These three simple steps describe precisely what takes place in the heat treatment process. Yes, it's that simple, but so often misunderstood due to bad habits, bad information, or poor shortcuts. The following steps will set the platform for your heat treating understanding. Try to lay aside the way you heat treat now and set the following as your new standard.

Temperatures to effect hardness changes range from 2400° F to -320° F (1315° C to -196° C). Some processes require fast heating and some require slow, even heating. The key to success is to follow the manufacturer's recommendation. But be aware that the temperature used for hardening most tool steels is very critical, and tends to be even more critical as the chemistry in a steel becomes more exotic and involved. Extensive tests have been performed on how temperatures and times affect the structure of metals.

To give you an example, tests have been performed on 10 blocks of M2 high speed steel. The size of the blocks tested were 1" × 1" × 1" (25mm × 25mm × 25mm). The test objective was to see what effect a variable soak time had on the heat treat cycle on ten identical blocks. The furnace was properly calibrated and the only variable was the time of soak. We allowed the first block to soak at the austenizing temperature for $4\ ^{1}/_{2}$ minutes, which was the prescribed optimum time. (*Author's note*: There are only two metallurgical terms, *austenite* and *martensite*, that you need to be familiar with in order to understand the heat treatment process. These terms are discussed fully in layman's terms in Chapter 5.) The blocks were removed from the furnace individually at 30 second intervals and a microscopic examination of the micro structure of each block was made. It was determined that a small degree of overcooking started to occur at $1\ ^{1}/_{2}$ minutes past the $4\ ^{1}/_{2}$ minute mark, or at 6 minutes. Observations of the eighth piece, which had soaked $3\ ^{1}/_{2}$ minutes longer than the proper time, displayed a well deteriorated structure which would have given extremely poor results if it had been used in any tool application. It had lost about 1 point on the Rockwell scale and showed a definite loss of magnetism.

The tenth piece was considerably worse and considered to be junk steel. Tests on highly alloyed tool steels like D2 won't show this same type of extreme because soak times are dramatically longer. But the potential exists and is very real in nearly every grade of steel. It's just a matter of being oversoaked in minutes instead of seconds. The lower alloyed tool steels, such as O1 or W1 can be oversoaked but are very forgiving. This should not be taken to mean it shouldn't be a concern to you, but a fair warning to be aware of your process. Generally speaking, these lower alloy grades are most often found to be undercooked, as they are favorite grades for quick repairs or for the quick tool need that is produced with a torch or forge. It's not wrong to use them that way as long as you are aware the tool is not likely to perform to its maximum ability. Be sure to read the recipe process for these grades and decide the risk levels you are comfortable with. Above all else, make sure that you temper the steel properly as recommended by the manufacturer.

As you can see, time is equally important and needs your fullest attention or the steel can be either overcooked or undercooked when passing through the austenizing transformation phases. Time at temperature can range from seconds to 72 hours depending on the mass and process incorporated. The higher the alloy, again the more critical the accuracy becomes. Interestingly, by the same type of testing discussed on the M2 test above, temperatures in excess of 1888° F (1031° C) will begin overcooking D2 tool steel, and temperatures under 1827° F (997° C) cause poor austenization and start showing undercooked D2. That is a very narrow temperature range, but not a mystery. All you need to learn are the rules of the process and to live within them.

Transformation to proper hardened tool steel is the result of controlled removal of the heat from the metal, and has dramatic effects on the outcome. You can cool the metal, called quenching, from high temperatures by using water, oil, or air to cool or remove the heat and cause the transformation to take effect. Water is the fastest quenching method and either it can be sprayed on the part or the part can be dipped into a bath of water. Usually salt is added to the water to make a brine mixture. The brine benefits the part's surface by coating the part during the quench, which is detailed later in Chapter 13 dealing with water hardening tool steels. Oil is also used much more extensively, since it not only has a higher viscosity and promotes slightly safer heat treatment but also cools the metal more slowly than water. Air is the slowest coolant, but gives the best security by lessening the thermal shock placed on the steel. It also lessens the stress internally inherent in all hardened metals.

Heat treatment is not restricted to ferrous metals. It can be used on certain aluminum, copper, and titanium grades as well. This study will center on only the tool steels and alloy steels. This text is centered on sound heat treatment practices and, for the most part, should be sufficient for toolmakers and engineers to grasp a thorough understanding of what goes on in the process of heat treating.

Chapter 3

The Basic Furnace Room Tools

As mentioned in the Preface, this book will not address the multitude of different types of furnaces available on the market today. It will, however, address the condition and the need for certain accessories used in your heat treatment process. With some minor improvements and good basic understanding of the tools you need and use, you can often improve your chances of success dramatically. Since it is physically impossible to be there with you to see your particular circumstances, certain assumptions are made, and you will need to compare and evaluate to see exactly where you are in relationship to the suggestions given. If your standards are better and you have better equipment to work with, great! You should be capable of even more success. In this chapter we will study the various pieces of equipment that will help you do a proper job.

The Furnace

Most tool rooms and shops today have nonatmospheric furnaces available to heat treat their tool steel. The high cost of purchasing a vacuum