TECH - TOPICS

Published as a service to the industry by
LATROBE SPECIALTY STEEL COMPANY

LATROBE SPECIALTY
STEEL COMPANY

Latrobe, PA 15650-0031 USA

Bulletin 102

Heat Treating Practices

Heat Treating is arguably the most critical operation in the manufacture of components made from tool steels. Improper heat treatment will result in degraded properties and reduced service life for the finished tooling.

For optimum tool performance, follow the practices detailed in this bulletin and the recommended heat treating temperatures and practices presented in the data sheet for each grade of steel.

HARDENING

The hardening process for virtually all tool steels consists of four steps:

1. Preheating 2. Austenitizing
3. Quenching 4. Tempering

As the steel progresses through these steps, the atoms of iron, carbon, and alloy elements rearrange in relation to one another. The final arrangement of these atoms determines the properties of the steel; properties like hardness, strength, and toughness.

Although surface oxides, which may form on the parts, is visible, the important changes that occur in the steel occur on an **atomic scale**. As such, these changes are not visible without the aid of a microscope.

Because the changes that occur are essentially invisible, the heat treatment process is controlled by two variables: **temperature** and **time**. Thus, it is essential that temperature and time measurements be accurate through all stages of the heat treatment process. In this regard, the actual temperature of the part is the important temperature; not the overall furnace temperature. Furnaces seldom maintain a uniform temperature in all areas of the heating chamber. Thus, a single furnace control thermocouple will seldom provide an accurate measurement of the part temperature. ***Whenever possible, a separate thermocouple should be placed inside or on the part being heat treated to provide an accurate measurement of the actual part temperature***.

SURFACE PROTECTION

The first important consideration in heat treating any tool steel is protection of the surface of the tool. Almost all tool steels can have carbon removed from their surfaces (*decarburization*) by heating them above about 1500°F (816°C) in the presence of air. Similarly, carbon can also be added into the surface (*carburization*) if the steel is in contact with a high-carbon source at elevated temperature. If a surface is decarburized or carburized, it will not exhibit the proper hardness after heat treatment. Decarburization and carburization can be prevented using one of four methods:

1. Use a furnace that produces either a vacuum or an oxygen-free atmosphere inside a sealed heating chamber.
2. Use a molten salt bath that is properly rectified (deoxidized) to prevent decarburization.
3. Use an air furnace that contains an interior muffle that can be filled with inert gas. Some special muffles generate an inert gas as they are heated.
4. Insulate the workpiece from the air by one of several methods:
   - A. Wrapping in an air-tight envelope of stainless steel foil.
   - B. Painting or plating the surface with high-temperature paint or metallic plating.
   - C. Packing the tool in box of inert material.

PREHEATING

Metallurgically, preheating takes no part in the hardening process; but is included in the heat treatment because it minimizes the two types of stresses, which occur in a part when it is hardened.

The first type of stress is thermal expansion stress. As the steel is heated, it expands. If a cold part is placed into a very hot furnace, the sudden shock heating of the surface can result in distortion or cracking.

The second type of stress is metallurgical. In the annealed steel, the atoms are in a body-centered-cubic (*bcc*) structure known as **ferrite**. When the Ac1 critical temperature is reached during heating, the atoms rearrange into a more tightly condensed, face-centered-cubic (*fcc*) structure known as **austenite**. This results in a volume *decrease* in the steel.

If preheating is not used, the thermal expansion stresses and the metallurgical stresses can occur simultaneously in the part. These stresses can result in distortion and in the worst case, cracking of the part.

For most cold work tool steels, a single-step, *subcritical* preheat is typically used. The steel is heated to just below the Ac1 critical temperature and the only stresses that occur are thermal expansion stresses. After the part is uniformly heated through (equalized) at the preheat temperature, it can be rapidly heated to the austenitizing temperature. In the process, only the metallurgical stresses occur. The typical preheat temperature range for this steel is about 1200 -1400°F (649 - 760°C).

For most hot work tool steels, some highly-alloyed cold work tool steels, and all high-speed steels, the single preheat temperature may be slightly below or slightly above the Ac1 critical temperature. Because the austenitizing temperatures for these steels are high, preheating to a temperature just above the Ac1 critical can be beneficial. The transformation from ferrite to austenite and the accompanying metallurgical stresses occur while the steel is being heated slowly and uniformly. The typical preheating temperature for these steels is 1500-1600°F (816-871°C).

SINGLE-STEP PRACTICE:

Heat to the recommended preheat temperature at a rate that does not exceed 400°F per hour (222°C per hour), and hold until the part is equalized.

For large or complexly-shaped parts, a two-step preheat is often used. The first preheating temperature is below the Ac1 critical temperature, and the final preheating temperature is just above the Ac1 critical temperature.

TWO-STEP PRACTICE:

Heat to each preheat temperature at a rate that does not exceed 400°F per hour (222°C per hour), and hold until equalized. Typical two-step preheat temperatures are 1200-1300°F (649-704°C) and 1500-1600°F (816-871°C).

AUSTENITIZING (HIGH HEAT)

The high heat, or *austenitizing* temperature is used to fully rearrange the atoms to the austenitic (*fcc*) structure, and to dissolve the alloying elements (most of which are in the form of alloy carbides) into the austenite.

Austenitizing is a temperature-time dependent process. However, temperature has a far greater influence than time. In developing heat treating data for each grade of tool steel, the manufacturer carefully determines the proper austenitizing temperature range for that grade. As a result, it is difficult to overheat a piece of steel by austenitizing for too long a time, *providing that the temperature is within the recommended range.*

Lower austenitizing temperatures result in higher toughness in the final product. However, if too low a temperature is used, the alloying elements will not be properly dissolved, and the steel will not exhibit the desired properties.

Higher austenitizing temperatures result in higher final hardness and improved elevated-temperature properties, such as hot hardness. However, too high a temperature will result in grain growth or even melting.

Overheating usually occurs as a result of excessive temperature, not excessive soaking time. Soaking time problems are usually undersoaking rather than oversoaking. Undersoaking results in the alloying elements not being properly dissolved and the hardened steel will not exhibit the desired properties.

When higher than normal austenitizing temperatures are used, either intentionally or inadvertently, the soaking time becomes increasingly more critical.

These concerns emphasize the previously discussed need for accurate temperature control in the heating medium, and diligence in controlling the heating times.

Because molten salt conducts heat very quickly, for austenitizing temperatures of 2000°F (1093°C) and higher, salt bath temperatures should be about 25°F (14°C) lower than furnace temperatures.

AUSTENITIZING PRACTICES:

After preheating, heat rapidly to the austenitizing temperature and equalize. Soak at the austenitizing temperature for the appropriate time based upon the type of steel and the size of the tool.

The following soaking time guidelines apply for the three families of tool steels.

Carbon and Low-Alloy tool steels are austenitized at relatively low temperatures and depend only upon the solution of iron carbides in the austenite for their hardening. The iron carbides readily dissolve in the austenite. Therefore, there is considerable latitude for both temperature and time in heat treating these steels. Soaking times are short, typically only 5 minutes per inch (25.4mm) of thickness, although longer times are not detrimental because of the relatively low temperatures.

Cold Work and Hot Work tool steels contain alloy carbides, which do not dissolve as readily in austenite. Therefore, soaking times must be longer to avoid undersoaking. The guideline these steels is to soak at temperature for 30 minutes for the first inch (25.4 mm) of thickness, plus 15 minutes for each additional inch (25.4 mm) of thickness, with a minimum soaking time of 30 minutes.

High-Speed steels, and some specialty tool steels contain complex carbides, which contain significant amounts of vanadium. These carbides do not dissolve to an appreciable extent until the temperature is very near the melting temperature of the steel. *Thus, very accurate temperature control is mandatory for austenitizing these steels*. Overheating these steels will literally result in localized areas of melting (*incipient melting*) at grain boundaries.

Because the austenitizing temperatures are so high, very short soaking times are used for these steels. The guidelines relating low and high austenitizing temperatures and product toughness apply, but soaking time guidelines are more elusive. Soaking times of about 5 minutes are common, but experience and product performance results are the best guides for determining the proper austenitizing soak time for each application.

QUENCHING

Tool steels become hard when the austenite transforms to *martensite* as the steel is quenched from the austenitizing temperature. During quenching, the atoms rearrange from the fcc austenite to a body-centered-tetragonal (*bct*) structure. The rapid heat removal causes carbon atoms to become trapped in highly-stressed positions among the other atoms. These inter-atomic stresses give the steel its hardness and strength.

In cooling from the austenitizing temperature, the steel must pass rapidly through the critical temperature range of about 1300 to 1000°F (704 to 538°C). If the quench rate through this range is too slow, products other than martensite form and the steel exhibits lower hardness. The chemical composition of the steel determines the upper and lower limits of this critical temperature range and the critical quench rate required through this range.

Once the steel is quenched through the critical range, hardening becomes more dependant upon temperature than time. The actual transformation from austenite to martensite does not begin until the steel cools to below about 600°F (316°C). Highly-alloyed steels can dwell in the temperature range of 1000 to 600°F (538 to 316°C) without detriment and special interrupted quenching techniques, such as martempering and salt quenching, can be used.

By interrupting the quench and equalizing above 600°F (316°C), the final quench can be at a less severe rate, which results in lower quenching stresses, less geometric distortion, and lower risk of cracking.

During the quench below 600°F (316°C), the atomic rearrangement from austenite to martensite results in a volume *expansion*. This expansion results in high, but inevitable stresses in the part. Under adverse circumstances, these stresses can result in warping or even cracking of the part.

QUENCHING PRACTICES:

Air Cooling: Some steels with high alloy content can be hardened through moderately thick sections by cooling in still air. These are the air hardening tool steels and the relatively slow quench results in a minimum of distortion.

Oil and Salt Quenching: Most tool steels require a fast quench rate, approximately 300°F (167°C) per minute, achieved by quenching in oil. However, if oil quenching is continued to below about 600°F (316°C) the fast rate can result in greater geometric distortion, and carries a higher risk of cracking. Interrupting the oil quench will minimize distortion and cracking risks. This involves quenching in oil until the part is below about 900°F (428°C), then removing the part from the oil and continuing the quench by cooling in still air. At 900°F (428°C), the part is no longer red in color, so this is known as *quenching until black.* For large or intricately-shaped parts, interrupted oil quenching is normally recommended to prevent cracking.

Even faster quench rates can be achieved by quenching into molten salt, because salt conducts heat faster than oil. When quenching in salt, allow the part to equalize at the bath temperature, then remove it and cool it in still air.

Pressurized Gas Quenching: Some vacuum furnaces contain an integral oil quench, but in most, quenching is performed by flooding the vacuum chamber with cold nitrogen gas at pressures ranging from 1 to 20 bars (about 1 to 20 times atmospheric pressure).

Contrary to common belief, it is not necessarily true that higher quench pressure results in a faster quench. The actual quench rate depends upon several factors: the gas pressure, the volume and direction of gas flow in the chamber, the efficiency of the gas heat exchanger, and the size (mass) of the workload. A high-pressure furnace with too large a workload or an inefficient heat exchanger may actually quench more slowly than a lower-pressure furnace that is properly loaded and well maintained.

Quench rates in vacuum furnaces should be monitored with thermocouples attached to the parts to insure accurate results. *As with all quenching, the quench rate to below about 1000°F (538°C) is critical.* At the present time, some tool steels, which require oil quenching to achieve maximum hardness, do not achieve maximum hardness when quenched with pressurized gas in a vacuum furnace.

TEMPERING (DRAWING)

Upon completion of hardening, the as-quenched steel is highly stressed and brittle, and must be handled carefully. Tempering, or *drawing*, is performed to improve the toughness and ductility. By heating the steel to and holding it at an intermediate temperature, the inter-atomic stresses in the martensite are partially relieved, and the tool becomes useable. For some tool steels, such as the high speed steels, tempering at a temperature above 900°F (482°C) actually increases the hardness through a process known as *secondary hardening*. During secondary hardening, additional alloy carbides form in the steel, and increase the hardness.

Multiple tempering treatments are used to eliminate or reduce any *retained austenite*, which may not have transformed to martensite during the quench. The second tempering treatment tempers any *secondary fresh martensite*, which formed during cooling from the first temper.

Tempering should be performed as soon as the part cools to about 150-125°F (66-51°C) during the quench. This temperature range is traditionally known as *hand warm* because it is when the part can be held in the bare hand without burning.

If tempering is performed before the part cools to hand warm, there may be insufficient transformation to martensite, and there is a high risk of cracking the part when it cools from the tempering treatment.

If the quench is continued below the hand warm range, there is a greatly increased risk of quench cracking the part. A similar risk of cracking exists if the part is allowed to sit at ambient temperature between the quench and the first temper.

TEMPERING PRACTICE:

Temper as soon as the part cools to 150-125°F (66-51°C). Heat to the tempering temperature, equalize, and hold at temperature for a minimum of two hours. Then air cool to ambient temperature. For multiple tempers, air cool to ambient temperature between each two-hour temper.