Basics of Austempering

— A Thermal Hardening Process for Fasteners over HRC40

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What do many lawn mower blades and automotive spring steel clips have in common? When considering their applications, probably very little, but in their product realization, they likely have both employed Austempering (a heat treating process) as their method for strengthening and toughening. Although over 75 years old, Austempering is a heat treating process that has really only become practically viable and commercially employed in the last 40 years. Austempering will likely never supplant conventional quench and tempering processes for the majority of threaded fastener applications, yet some of the advantages are so compelling that there will always be interest and activity in expanding the current application field. At hardness levels above 40 HRC, Austempered parts demonstrate improved mechanical properties such as toughness, ductility and strength over their quench and tempered counterparts of comparable hardness. Austempered parts undergo significantly less distortion, which reduces the subsequent cost of post heat treatment remediation.

Since this technology has direct application for the fastener industry, both now and well into the future, it is advisable for practitioners of the industry to have an understanding of the basics and enough information to consider what future possibilities might be waiting out there. The goal of this article is to provide a simplified explanation of this complex process and to explain some of its more compelling advantages.

History

In 1933, two researchers for the **United States Steel Corporation**, **Edgar C. Bain** and **Edmund S. Davenport,** patented a new heat treating process. Unlike the conventional quench and temper process, which produces the hard and strong structure known as Martensite, their process produced an almost equally hard and strong structure they called Martensite-Troostite. Later this structure would be called Bainite after E.C. Bain and the process they patented called Austempering. Although there were several military uses that appeared during World War II, the lack of commercial availability and safe processing equipment would prevent any real commercial adoption until the 1960s. In 1962, developments would be made in furnace technology that propelled Austempering to become a commercially available alternative to conventional quench and tempering, especially in the automotive, agricultural and USA military equipment industries. Advancements in equipment technology have continued to the present day, furthering the breadth of potential applications that can be processed by Austempering.

Basic Metallurgy

To understand the advantages of this process, one must possess a basic understanding of a few metallurgical principles. First, heat treating processes are time-dependent, transformation processes. That means that by the nature of the process, the item being heat treated is being changed (or transformed) internally to a different structure with a different set of physical properties over some measurable length of time. Although the analogy is not perfect, it's a little bit like scrambling an egg, you must first thoroughly mix up the egg before you can cook it to make something you can eat. In both states, the egg mixture and the cooked egg, the composition is identical, but the form and physical properties are quite different.

Like the scrambled egg analogy, heat treating generally starts from an established point. This is getting the steel into one homogenous solid phase. This happens to be the high-temperature phase of steel, also known as Austenite. In practice, this phase is obtained by placing the parts in a furnace and heating and holding them at a specified temperature long enough that the internal structure completely becomes Austenite. This is normally referred to as Austenitizing. Every steel will have a slightly different minimum temperature requirement to reach this point, which is why, in practice, heat treaters vary their process "recipe" and generally operate within specified temperature ranges as opposed to a single definitive temperature.

Figure 1 shows a fundamental metallurgical diagram, the Time-Temperature-Transformation (TTT) Diagram for steel. Although every steel composition will have a little different TTT diagram, this one is intended to demonstrate the general principles. The diagram shows temperature along the Y axis and time along the X axis. In the diagram is a line or band that resembles a human nose in profile that converges near the bottom of the diagram in a band that goes straight across the plot. This nose-like band rep-

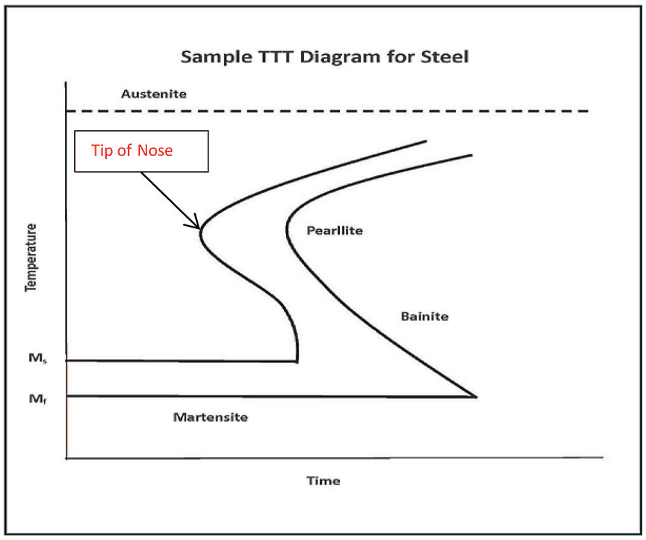

Fig. 1 — "Generic" sample TTT Diagram for steel tip of nose.

resents the time and temperature that the steel begins to transform from austenite into a new structure. Depending on the length of time and at what temperature this occurs, a variety of different structures ranging from those producing "low mechanical properties" to "high mechanical properties" can be obtained. Very quick (almost immediate) transformation processes to the left of the "nose" are where the conventional quench and temper processes are done and are intended to form a structure called Martensite. Martensite is strong and hard and this is the process most commonly employed to strengthen a fastener. The straight band along the bottom of the diagram represents the temperature at which transformation to Martensite begins and ends (the top line M_s designates the Martensite Start temperature and the lower line, M_f, the Martensite Finish temperature). If longer times are employed, transformation occurs to the right of and above the "nose", and softer, less hard structures known as Pearlite are formed. This is what occurs when parts are annealed.

Another structure that provides distinctly different physical properties is Bainite. Bainite lies between Pearlite and Martensite and exhibits properties somewhere between the two. Bainite has two distinctly different forms, Upper Bainite and Lower Bainite. Lower Bainite is the preferred form as its physical properties more closely resemble tempered Martensite, meaning they are strong, tough and hard. However, referring back to **Figure 1**, to obtain this structure one must employ a process that makes it past the tip of the "nose" on the TTT Diagram yet not begin the Martensite transformation. The process that accomplishes this is the Austempering process patented by Bain and Davenport.

Austempering Process

Figure 2 illustrates the Austempering process graphically on the TTT Diagram. Austempering starts out like any other heat treating process. The parts must first be Austenitized or raised in temperature and remain long enough at the temperature that the steel fully transforms to Austenite. Like all heat treating processes, this first step is important and the Austenitizing temperature must fulfill established parameters for different steel types to allow for the entire contents of a load to reach the desired temperature and fully become Austenite. Once the parts reach this temperature and condition, the next steps will determine how the steel will be transformed. They will be cooled (quenched) either rapidly as occurs in hardening processes or slowly as occurs in annealing processes.

In the case of Austempering, this is where the process gets a little tricky. The cooling rate must be fast enough that the parts will make it past the tip of the "nose" represented on the TTT Diagram without beginning transformation, but must be stopped short of the Martensite Start temperature. This is usually accomplished using a nitrate/nitrite molten salt bath that is held at a temperature below the tip of the "nose" but above the Martensite Start. The parts are held at

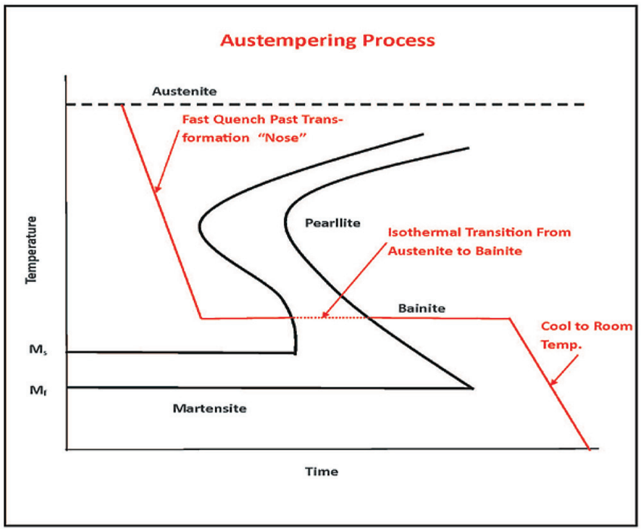

Fig 2 — Illustration of the isothermal cooling, Austempering process.

this temperature long enough to fully transform to Bainite and then are removed and left to cool to room temperature. Depending on the specific steel, this transformation may take a matter of minutes or even a number of hours. The constant temperature of the salt bath holds them at this same temperature over the entire duration of transformation. This is known as isothermal cooling. Shortly after the parts come out of the salt bath, they are ready to be cleaned in water to remove all of the accumulated residual salt.

To understand the differences of the two processes, consider **Figure 3**, the TTT Diagram of 8640/8740 alloy steel. The red line represents a quench and temper process and the blue line an Austempering process (note: these are examples for illustration purposes and do not represent a specific heat treating "recipe"). Tracing the red line first, the parts start as Austenite at about 1500°F and are quenched in an oil bath, which is at about 200°F. In this process, the Austenite is transformed to Martensite. Extending a line down to the X axis, one sees that the process lasted about two seconds. Remembering that untempered Martensite

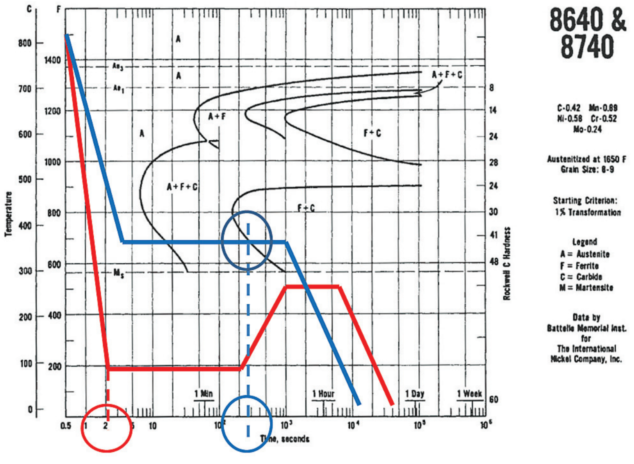

Fig. 3 — Comparison of Q&T Process to Austempering process using 8640 TTT Diagram.

is brittle and not practically useful, the parts must be tempered, or moderately heated back up and held at that temperature for a time, which is what the remainder of the red trace represents. Turning to the Austempering process depicted by the blue line, one sees that the starting point is essentially the same. In this example, the parts are dropped into a salt bath held at 700°F. They are allowed to remain there until they have been fully transformed to Bainite and then allowed to cool to room temperature. Again, extending a line down to the X axis from the end of the transformation line, one sees that the transformation completed in about five minutes. Naturally the heat treater will likely leave the parts in significantly longer than this to assure complete transformation, especially since one of the advantages of Austempering is that there is no penalty to leaving parts in the salt bath longer than actually needed. Problems, however, do arise if the parts are not given sufficient time to transform. As the diagram illustrates, the two processes are clearly quite different, but highly dependent on understanding the TTT information.

Advantages

Austempering provides a number of compelling advantages. These include:

Less Distortion. Depending on conditions such as temperature or pressure, materials may exist in different states (or phases). Take for example water, at room temperature it's a liquid, but when the temperature goes down, that liquid turns to a solid (ice). In many materials and especially in metals, depending on the conditions there can be a number of distinct and different solid phases with completely different properties. One of the best known examples of this phenomenon is carbon. It has two solid phases, Graphite which is best known for its use as pencil lead and Diamond, which, of course, is "a girl's best friend". At an atomic level, each of steel's solid phases (it has several) is ordered into a specific crystal structure. There are actually 13 different crystal structures that a material may take, but each phase will only exhibit the one that is unique to it. As previously discussed, any steel that is heat treated starts out by Austenitizing (or raising the temperature until the entire structure is Austenite.) The crystal structure adopted by Austenite is face-centered cubic. In the conventional quench and temper process, the Austenite is transformed to Martensite, which is body-centered tetragonal in crystal structure. There is a volumetric expansion that occurs from the face-centered cubic transition to body-centered tetragonal. Depending on the geometry of the part, this volume change will not occur simultaneously creating uneven stress distributions that can lead to distortion. In Austempering, however, because the part is held isothermally throughout the transition to Bainite, this effect is drastically reduced and the distortion is less. It should be noted that there will still be distortion, but in many cases it is dramatically reduced so that corrective procedures required with a quench and temper process become minimal or unnecessary.

Toughness. With respect to threaded fasteners, it is commonplace to consider strength and hardness, but all too often completely ignore toughness. Toughness is the ability of a material (or part) to absorb energy and deform without fracturing. In a practical sense, this is a measure of brittleness. Austempered parts exhibit higher toughness at equivalent hardness levels to quench and tempered parts. For common threaded fasteners below HRC40 hardness this may not be that significant, but for high-strength threaded fasteners above HRC40, this is extremely beneficial.

Strength. The Martensite formed in the quench and temper process produces the highest strength parts. However, the form of Martensite developed immediately after quenching (untempered Martensite), although very hard and strong, has very little toughness and is impractical to use in this condition. Therefore, Martensitic structures must be tempered to make them practically useful. This is easy enough to achieve with a tempering operation, but with the consequence of dropping the hardness level. Austempered parts achieve strength levels nearly equal to or slightly higher than tempered Martensite without the need for a separate operation and the subsequent reduction of strength. Although the Austempering process does not require a tempering operation, the cost savings are most likely offset by the more limited commercial availability and controls required to properly operate the process. However, in many cases Austempering does provide the shortest overall time to through harden a part, which has potential for future lean or improvement initiatives.

Hydrogen Embrittlement Risk. It has been argued that Austempering provides an answer to the vexing problem of hydrogen embrittlement risk for parts over HRC40. Although there are some promising reasons to remain hopeful, industry experts consider this position to be controversial and studies are currently being conducted to gain a clearer understanding in this area. Therefore, for now risk management procedures should not change, which includes avoiding electroplating parts above HRC40. In fact, the limited number of Austempered threaded bolts and screws above HRC40 in service today are performing their duties with no finish and in noncorrosive environments.

Fatigue Improvement. Austempered parts often exhibit favorable improvement in fatigue life over parts of equal hardness and strength processed using a conventional quench and temper.

Disadvantages

Unfortunately, the adage that "if it sounds too good to be true, it is" exists very much in the natural world and is true here. Austempering, although providing some compelling advantages, also has some limitations or disadvantages that will prevent this method of heat treating from a wholesale replacement of conventional quench and temper methods.

The greatest limitation is that for Austempering to work, one must be able to miss the "nose" on the TTT diagram and prevent transition to structures inferior in strength to Bainite and Martensite. This means that the material must respond quickly enough to the quench medium to accomplish this. In Austempering, the quench material must also be capable of being held at a high enough temperature to arrest Martensite Start transformation. Typical quench materials that give the "speed" necessary to cool the part down quickly normally don't also possess this temperature stability property. This presents a feasibility challenge or makes the process completely impossible for many steel and alloy steel grades. Therefore, the most significant disadvantage is that Austempering will not work with every steel type, which may in fact limit the process to only a select few options of threaded fastener grade steels. In a similar vein, this quench limitation may also impact the size of a part or section that can be processed. Again, the quench has to be fast enough to cool the entire part, all the way to the center as it passes the tip of the "nose" of the TTT diagram. This may produce limitations of how thick the sections may be that can be transformed using this process. For threaded bolts and screws this is generally considered to be a maximum of M16 or 9/16". For this reason, the most common fastener applications that employ Austempering are not threaded bolts and screws, but rather fasteners with thin cross sections such as washers, clips and springs.

The other disadvantages tend to be with the process equipment. Because the process requires a molten salt quenching bed, the equipment is more specialized and the available industry capacity is simply not as widespread as capacity for quench and tempering. Additionally, these molten salt beds can be thorny and have some inherent operating risks. Although many of these risks have been addressed with equipment innovation, heat treatment purveyors will surely consider these issues and for some deter them from adding the process to their existing capabilities. As a result of these issues, Austempering capacity is still very much in the minority to quench and tempering, making it generally more expensive for threaded bolts and screws.

Future for Fasteners

Austempering will continue to be a primary process technology for manufacturers of springs, spring metal clips, blades, gears and other parts that require high strength and superb toughness. However, does this process provide an opportunity, yet mostly untapped, for high-strength threaded fasteners with hardness limits above HRC40? Only time will tell. Nevertheless, providing an option for high-strength threaded fasteners above HRC40 that exhibit the improved physical properties experienced by Austempering compared with conventional quench and temper methods is quite intriguing and a field that deserves further study.

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For further discussion, contact **Laurence Claus** by email at **laurence@nnitraining.com**. Or to receive additional technical information on the basics of Austempering for fasteners over HRC40, visit the NNI website below.
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