Quenched and Tempered Bar

Abstract

In-line quenching and tempering has allowed CMC Steel Arizona to have a higher-ductility bar at higher strength levels compared with classic rebar production, with a substantial reduction in alloy consumption. The results of implementing this process have ranged from improved bundle quality to combined high-strength and high-ductility steel.

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Strengthening in steel is generally achieved by adding alloys to the liquid steel, causing distortions of the molecular lattice. Some of the steel standards that are available are either very open on the chemistry requirements or else have no chemical restrictions at all. Two examples of such a standard are A615 and A706 for rebar production. The purpose of this paper is to describe quenched and tempered bar (QTB) as an alternate, cost-effective means of achieving the mechanical requirements of the standards by quenching a hot rolled bar to a surface temperature below martensitic transformation to increase the strength of the bar, and then tempering the martensitic surface of the bar to promote ductility. This paper considers the QTB overview, microstructural evaluation, implementation, quality assurance of the process, and the advantages and disadvantages of using QTB in place of a traditional, alloy-based process.

QTB Overview

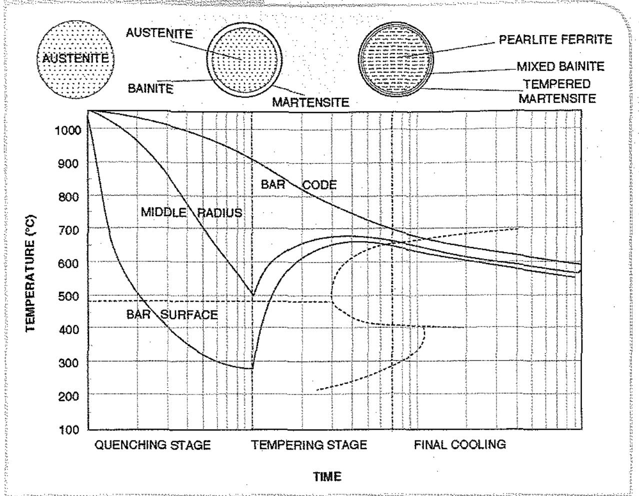
QTB is designed to be installed in-line with the rolling process. The hot rolled bar is fully submerged in water in order to rapidly cool the surface of the bar below the martensitic transformation temperature. This phase of the process creates a hardened "case" on the outside of the bar. The core of the bar remains austenitic. The residual heat in the core of the bar radiates out to the shell of the bar, tempering the newly formed martensite. During this time, the surface of the bar reheats to approximately 600–700°C. After the bar reaches its peak reheat temperature, it cools naturally until reaching ambient temperatures.

Figure 1 shows the typical cooling and reheating curves of the surface of the bar, the center of the bar and the midway point of the bar. The figure also shows the microstructure before quenching, after quenching and after tempering. The final bar has a pearlite core, a thin layer of mixed bainite and an outer shell of tempered martensite.

After the bar has reached ambient temperature, it behaves more like a composite material than a single, solid material. For example, steel-reinforced concrete has the tension-bearing properties of the steel and the compression strength of the concrete. Similarly, a QTB bar has the ductility of the core of the bar and the strength of the case of the bar. By reducing the alloy additions, the core of the bar is softer and more ductile than the fully alloyed counterpart. The tensile strength is determined by the combination of bar chemistry and the depth of quench achieved during the quenching phase of the process. The end result is that the elongation penalty is reduced when increasing yield and tensile strength, compared to traditional strengthening methods for hot rolled bar.

Steel that is manufactured from recycled scrap can face another challenge related to the raw materials. There are elements that can have significant impact to the mechanical properties of the steel that are

Figure 1



Thermal path of the QTB process.

present in ever-changing quantities in the scrap and in the final product. Examples of these elements are Cr, Ni, Mo, Co and W. The aim carbon for a typical QTB rebar application is between 0.25 and 0.30%. As a result, carbide-forming residuals have a lessened effect compared to when they are found in fully alloyed steel. Also, when using QTB, the mechanical properties are not determined by chemistry alone, so the operator is able to adjust the quenching phase of the process to adapt to the changes in chemistry. The process is able to absorb a wider range of residuals in the steel scrap compared to a more traditional process, while still achieving the strength aims of the standard being manufactured.

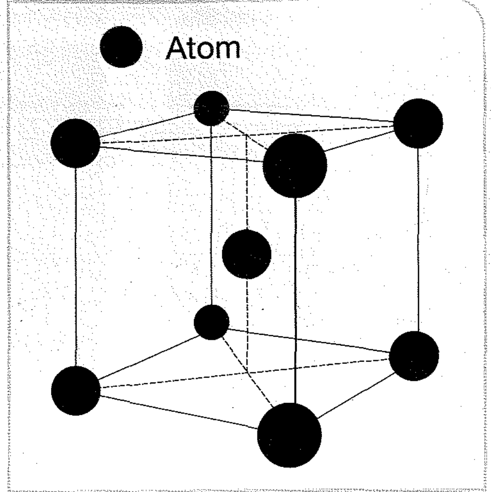
QTB Microstructural Evaluation

Steel is an allotropic material, meaning it can exist in different crystalline structures. Most "plain" carbon steel exists in the ferrite microstructure. It is magnetic, stable and, for the strength it imparts, it remains reasonably ductile. Because steel is allotropic, it can be heat treated to change the mechanical properties of the metal. An alternate steel microstructure that is also stable at ambient temperature is martensite. Martensite is stronger and harder than ferrite and has a correspondingly lower ductility. Figures 2 and 3 represent comparison renderings of the molecular structures.

The ferrite rendering (Figure 2) is typical of most carbon steels. The martensite rendering (Figure 3) is typical of the surface (case) of a QTB-treated bar. Tempering the martensite is necessary to reduce internal stresses to the newly formed martensite and to eliminate brittleness in the final bar. Comparison micro etches are shown in Figures 4 and 5.

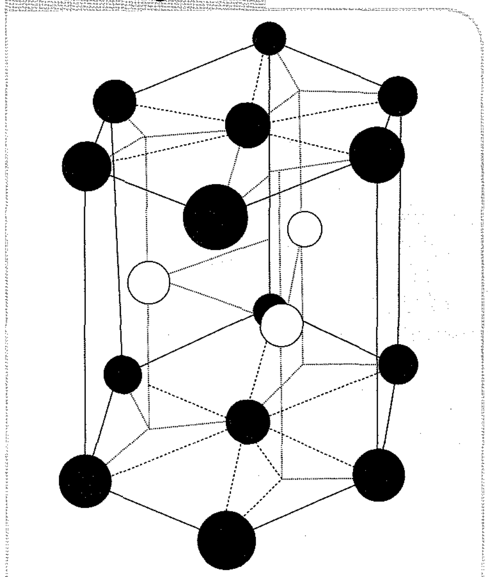
The core of the QTB-treated bar (Figure 6) is pearlitic. Grain refinement of the pearlitic core of the bar is observed compared with as-rolled bar of identical chemistry (Figure 7). This grain refinement contributes to the generally improved elongations of QTB-treated bar compared to the fully alloyed bar. This characteristic of the QTB-treated bar allows the

Figure 2



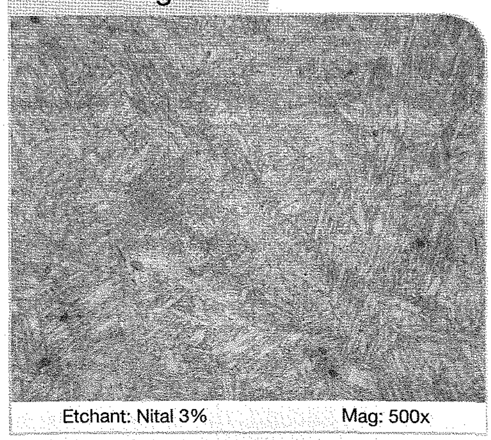
Ferrite "molecule" (body centered cubic).

Figure 3



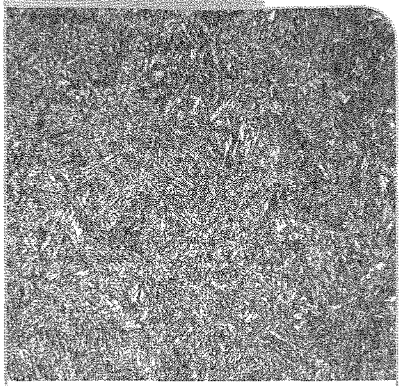
Martensite "molecule" (hexagonal bipyramid).

Figure 4



Crude (untempered) martensite.

Figure 5



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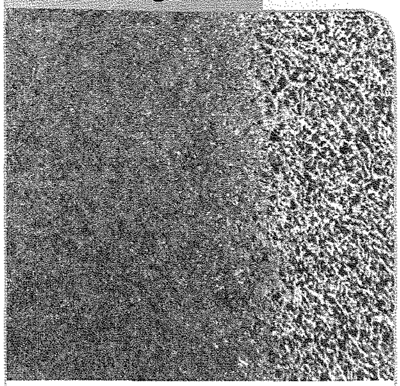
Tempered martensite.

Figure 6



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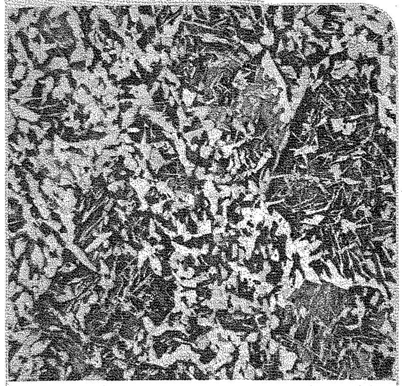
QTB 19-mm rebar case and core (1026 chemistry).

Figure 7



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As-rolled 19-mm rebar core (1026 chemistry).

manufacturer to increase the strength of the bar without sacrificing ductility of the bar.

Figure 8 is a micro etch of a QTB-treated bar showing the surface and the microstructural transition from surface to core. This sample is $^{3}/_{4}$ inch, grade 60 rebar with chemistry conforming to AISI 1026. Starting at the surface of the bar, the microstructure is tempered martensite. Moving toward the center of the bar, the tempering becomes more pronounced, which is viewed as a "softening" of the microstructure. At the transition from martensite to ferrite, approximately 0.035 inch below the surface, there is some evidence of mixed bainite. The pearlitic structure begins from this point through to the center of the bar.

Implementation in Production

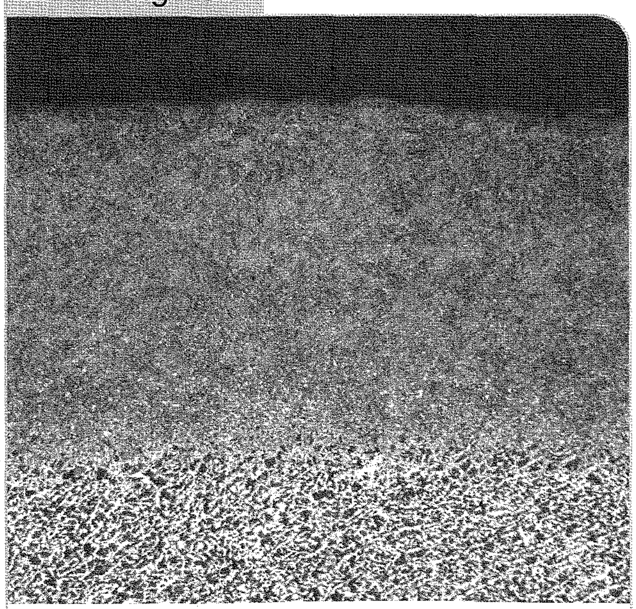
Implementation in production requires good water quality, a pumping system capable of handling the required volumes and pressures of water to achieve martensitic transformation, and a delivery system capable of evenly distributing water pressure and flow around the surface of the bar. Water must be delivered to the bar with enough pressure to prevent boiling of the water, generating steam at the bar surface. The part responsible for water delivery is commonly called a "cooler." Figure 9 is a schematic showing the water delivery to the bar for one cooler.

The cooler shown in Figure 9 is supplied with high-pressure water and is capable of sustaining high flowrates of water. In practice, multiple coolers are placed in series in order to obtain the desired quenching power of the system, as shown in Figure 10.

Water must be supplied with sufficient pressure to avoid steam generation — commonly called a "steam barrier." Steam acts as a thermal insulator and reduces the rate at which heat is extracted from the bar, which can prevent formation of martensite. Several considerations are needed to maintain effective quenching. A pumping system must be installed that can maintain the pressure and flowrates to create martensite on the surface of the bar. Second, the coolers must be sized appropriately for the bar being produced. In general, the closer the cooler inside diameter (ID) is to the size of the bar being quenched, the more powerful the quenching effect will be. When sizing the coolers, the engineer must also consider the challenges of threading the bar through the tubes. For example, a 2-inch ID cooler will be ineffective quenching a $^{1}/_{2}$-inch bar. A $^{7}/_{8}$-inch ID cooler will be difficult to repeatedly thread a $^{3}/_{4}$-inch bar through.

The quenching process starts when the bar enters the first tube. The next critical event is to provide the system with a definite stopping point to the quenching process. To do this, a different tube, called a "stripper," is installed in the quench box. The stripper functions the same way as a cooler, but the water is applied against the direction of travel instead of with it. The stripper uses a high-pressure water spray and air to blast any residual water off the bar, so that when

Figure 8



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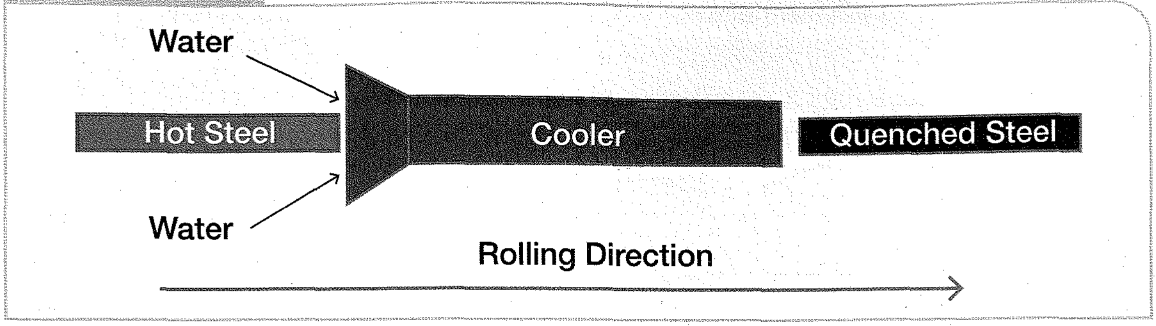
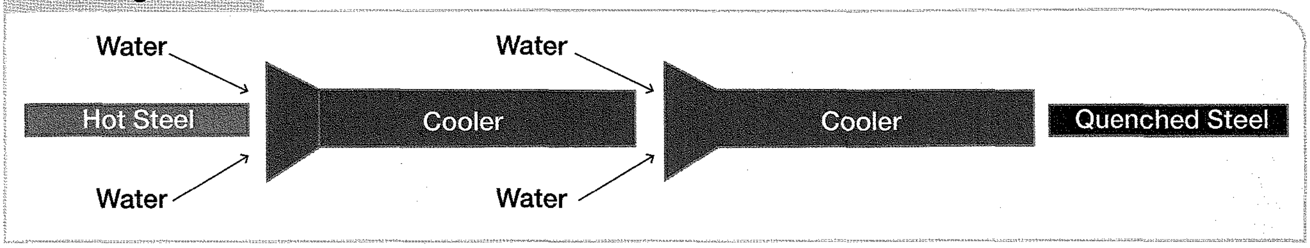
QTB surface, transition and core.

Figure 9



Representation of a functioning QTB cooler.

Figure 10



Representation of QTB coolers in series.

the bar leaves the stripper, it begins its tempering phase. Without the strippers, the quenching process is impossible to control. Figure 11 is an illustration of the workings of a stripper.

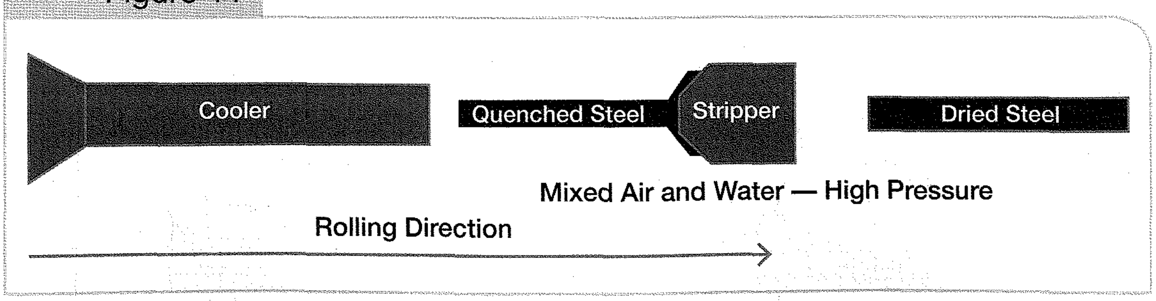
Quality Control of QTB

The QTB process has many input variables that must be kept in control in order to deliver the desired results. Some of these input variables are: finishing temperature of the bar, number of coolers, number of strippers, water pressure, water flow, finishing speed and cooler size relative to bar size. However, the process has only one output variable — tensile properties. Assuming a steady chemistry, the primary determining factor of the strength of the bar is the depth of the quench. As such, measuring the tensile properties of the bar gives a very good indication of the quenching system's performance at any given moment. As is described later, tensile testing is a poor indicator of future performance unless all input variables are tightly controlled.

The sum of all thermal inputs to the QTB process is the surface temperature of the bar as it leaves the quenching process. Anything that reduces quenching performance will result in an increase in surface temperature at the QTB exit. Anything that increases the quenching performance will result in a decrease in temperature at the QTB exit. Once the bar exits the quenching process, it reheats and enters the tempering phase. During the tempering phase, the bar will reach a peak reheat temperature, commonly called the "tempering temperature," and will then naturally cool to ambient temperature. In addition to the exit temperature of the quenching process, the tempering temperature must also be monitored.

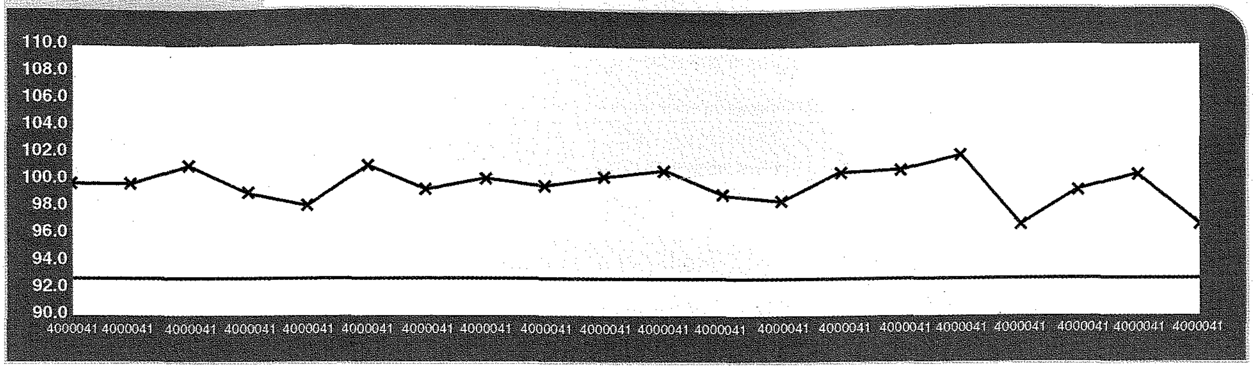
Given a constant chemistry, quenching temperature and tempering temperature, the mechanical properties of the bar will be remarkably consistent. Any changes in temperature at any point in the process

Figure 11



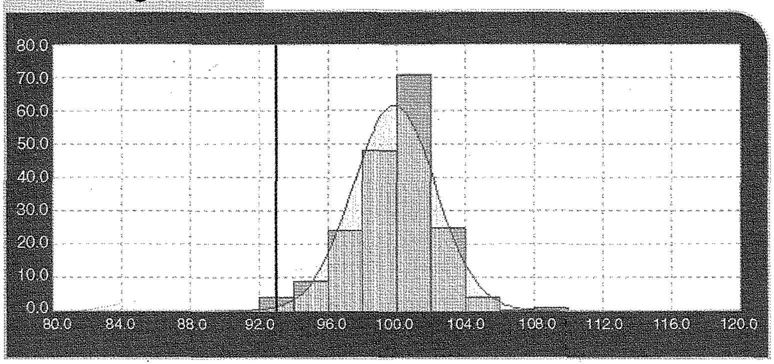
Representation of a functioning QTB stripper.

Figure 12



Control chart of tensile strength, #5 rebar, A615, grade 60.

Figure 13



Histogram of tensile strength, #5 rebar, A615, grade 60.

will appear as a change in bar strength. The control chart (Figure 12) illustrates both the ability of the QTB process to deliver consistent bar strength over time and also how the strength of the bar can suddenly change with no indication from the control chart.

Note that samples 1–16 stay within 2 ksi of 100 ksi, and sample 17 suddenly drops to 96 ksi. This indicates that something in the process shifted to a higher temperature, reducing the effectiveness of the quench. This also illustrates that simply measuring the tensile properties of the bar is not adequate to guarantee product quality or conformance to standards. When looking at longer-term data, the process is normal and relatively stable — even with some normal rolling process variation. The histogram (Figure 13) shows the distribution of 186 tensile samples of $^5/_8$-inch rebar.

A paradigm shift is required in the rolling operation. When running QTB, heats are not "made" or "missed" in the meltshop by the chemistry; they are "made" or "missed" in the heat treating, which is controlled by the rolling mill. As a result, process parameters that are normally not considered quality-related become quality parameters. For example, changes in finishing speed result in changes in tensile strength and yield strength. A paradigm shift is also required when setting internal grade specifications. QTB causes a higher increase in yield strength than tensile strength as it is applied. As a result, QTB causes a compression of the tensile-to-yield ratio when compared to a fully alloyed counterpart (Table 1).

When setting process parameters, the grade requirements must be fully understood. In cases like A615 rebar, where only minimum yield strength is specified, the critical specification is the tensile strength. If the tensile strength is above minimum, the yield strength will be safely above minimum. Elongation is rarely a concern due to the grain refinement discussed above. In cases where there is a maximum yield strength specified, the process must be carefully designed and controlled to maintain a consistent, on-target yield strength. When the tensile-to-yield ratio is specified, it becomes even more difficult to achieve the specification.

Quench Analysis

As mentioned above, the primary determining factor of the final properties of the bar is the quench depth.

Table 1

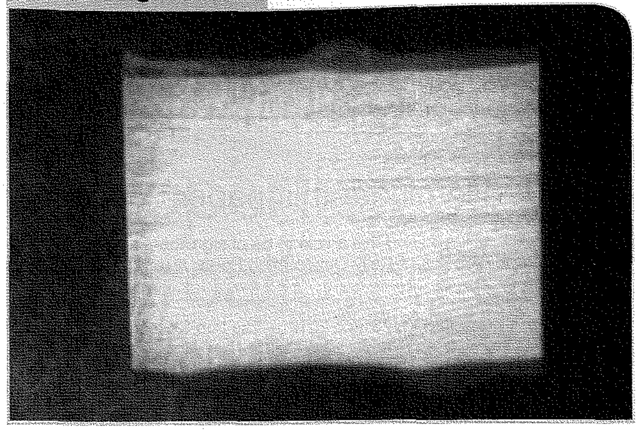
Comparison of Typical Properties: QTB vs. Fully Alloyed A615, Grade 60 Rebar

Process average sample	Carbon (no spec)	Manganese (no spec)	Tensile (min. 90 ksi)	Yield (min. 60 ksi)	Elongation (min. 9%)	T/Y ratio (no spec)
Fully alloyed	0.42%	1.00%	106 ksi	68 ksi	12%	1.56
QTB	0.26%	0.75%	103 ksi	86 ksi	15%	1.19

Figure 14

Quench depth cross-section.

Figure 15



Quench depth longitudinal section.

The ideal quench depth for a good balance between strength and ductility is 0.035–0.050 inch tempered martensite case. In addition, care must be taken to maintain an even quench depth around the entire bar. The quench depth will generally not follow the surface deformation of the bar, but will find an average path through the bar and stay very consistent unless something happens to change the process. Figure 14 shows this for a 3/4-inch rebar. Note the increased thickness of the case at the longitudinal ribs and the very circular pattern of the transition line (circle added for emphasis) in the cross-section. Note also in the longitudinal section (Figure 15) that the quench depth does not follow the transverse ribs, but rather forms almost a straight line through the bar.

When tensile testing, the bar will always break at its weakest point. There are fewer deformations where the mill markings are rolled into the rebar. When planning mechanical testing, samples must be chosen to put the mill markings between the grips so that the strength of the weakest part of the bar is measured. There is typically a 2–3 ksi difference in strength between samples that are pulled to break within the mill markings and samples that are pulled to break outside the mill markings.

Microhardness testing was performed on the cross-section of the bar to determine the degree of hardening achieved by the QTB process. The testing found that the case is measurably harder than the core of the bar, but it is not hardened to the degree typically considered as true case hardening. The hardness of the core averaged 215 HK, or a Rockwell 92 HRB equivalent. The hardness of the case averaged 315 HK, or a Rockwell 30 HRC equivalent. The hardness of the case is limited by the carbon content of the steel and also the degree of self-tempering from the residual heat radiating out from the core of the bar.

Summary

QTB is an alternate means of strengthening long bars by quenching the bars with water and then allowing the bars to self-temper the hardened case. The process

Table 2

Advantages and Disadvantages of QTB

Advantages	Disadvantages
Reduced alloy requirements to achieve product strength.	Additional equipment in the mill that requires maintenance and parts, such as pumps, piping, coolers, strippers, pyrometers.
Finer pearlitic structure of the core of the bar compared to as-rolled, fully alloyed counterpart.	Rolling parameters must be treated as quality parameters, because they directly affect bar strength.
Improved ductility at strength levels equal to or higher than the as-rolled counterpart.	Compressed tensile-to-yield ratio can make grades with yield strength maximums difficult to achieve.
Absorb a wide range of residuals in the steel from variations in the scrap steel supply.	Heats are made and missed in rolling operation, requiring a paradigm shift in rolling from operational throughput to operational consistency.
	Some downstream applications (such as threading) would not be able to use the quenched bar.

is performed in-line with the rolling process, after the finishing stand. The process is stable and controllable. Refer to Table 2 for a summary of the advantages and disadvantages of using the QTB process.

Acknowledgments

The author wishes to thank all of his colleagues within Commercial Metals Company, Danieli Corp. and METL Testing Laboratories. ✦

Nominate this paper

Did you find this article to be of significant relevance to the advancement of steel technology? If so, please consider nominating it for the AIST Hunt-Kelly Outstanding Paper Award at AIST.org/huntkelly.

This paper was presented at AISTech 2012 — The Iron & Steel Technology Conference and Exposition, Atlanta, Ga., and published in the Conference Proceedings.

From the AIST Staff

U. S. Steel

AIST Tours Pittsburgh-Area U. S. Steel Plants

On 28 June 2012, AIST staff had the opportunity to tour the Pittsburgh-area plants of **United States Steel Corporation's Mon Valley Works.** The Works consist of four facilities: the Edgar Thomson Plant in Braddock, Pa.; the Clairton Plant in Clairton, Pa.; the Irvin Plant in West Mifflin, Pa.; and the Fairless Plant in Fairless Hills, Pa. Thirty of AIST's 38 employees participated in the tour.

The tour commenced with a video introducing Mon Valley Works and providing an overview of the entire steelmaking process, from raw material to finished goods. The group was taken first to the Edgar Thomson Plant, followed by the Irvin and Clairton Plants.

Mon Valley Works has an annual raw steel production capability of 2.9 million net tons. **Edgar Thomson Plant,** located about 10 miles southeast of Pittsburgh in Braddock, Pa., is where basic steel production takes place at Mon Valley Works. Raw materials are combined in blast furnaces to produce liquid iron, which is then refined to create steel.

Irvin Plant, located in West Mifflin, Pa., rolls and treats steel slabs produced at the nearby Edgar Thomson Plant to meet customer specifications. Major sheet products manufactured at the Irvin Plant include hot rolled, cold rolled and coated sheet, in addition to products for special applications, such as embossed sheet, vitrenamel sheet and commercial bright sheet.

Clairton Plant is located approximately 20 miles south of Pittsburgh in Clairton, Pa., and sits along the west bank of the Monongahela River. The largest coke manufacturing facility in the United States, Clairton Plant operates 12 coke oven batteries and produces approximately 4.7 million tons of coke annually, serving customers in the commercial coke market as well as U. S. Steel's steelmaking facilities.

For many AIST employees, it was their first time in a steel mill of any kind. AIST staff who had experience in steel mills were able to help explain the various steelmaking areas and answer any questions along the way.

Jean Madeira, one of AIST's newest staff members, having joined the company in June 2012, said, "The most surprising thing about the tour was the heat." Krista McGhee, copy editor and graphic design assistant, who joined AIST in September 2011, noted, "It gave me an idea of the size of a steel mill, and a visual representation of what people are talking about."

Chris McKelvey, board services advisor, who has been with AIST since February 2011, was grateful to everyone who helped organized the plant tour. He said, "Seeing the processes involved in steelmaking first-hand really provided an understanding of, and an appreciation for, the hard work that men and women in the industry do. We saw sophisticated technology integrated with basic principles that have withstood the test of time. I think what impressed me the most was the equipment and machinery that are capable of withstanding extreme temperatures."

AIST would like to extend a special thank-you to United States Steel Corporation and all the U. S. Steel employees who took time out of their schedules to provide this tour to our staff.

AIST's tour was comprehensive, covering the majority of the steelmaking process. The following areas were part of the tour.

U. S. Steel – Mon Valley Works

Edgar Thomson Plant
- Top-blown basic oxygen process (BOP) vessels
- Dual-strand continuous slab caster

Irvin Plant
- 80" hot strip mill
- 84" and 64" pickle lines
- 84" 5-stand cold reduction mill
- Continuous annealing line
- Batch and open-coil annealing facilities
- 84" temper mill
- 52" hot-dip galvanizing line
- 48" hot-dip galvanizing/Galvalume® line
- Continuous terne coating line

Clairton Plant
- Coal unloading facility on the Monongahela River
- Coal blending and storage
- No. 8 and No. 9 coke batteries
- Tar storage tanks and coal chemical facility