Harden and temper with advanced process control – the modern quench and temper line

Kris Livermore – Director of Business Development, Thermatool Corp, USA

Driven by growing world demand for energy products and the challenge created when exploration and recovery introduces tubular products into harsh conditions, steel producers and processors of tubular products have been tasked with developing chemistries and grades of high strength steel to meet new standards of performance. Primary to this development of supply is the technology for the quench and tempering of API tubing and casing.

Process repeatability, and model-based process control stand as the most important new characteristics of value added processing for those looking to thrive and adapt in today's highly competitive markets. Possessing the technology to transform the material characteristics of steel in a controlled, repeatable process has been limited to older methods lacking computer controls in the quench and temper arena. The primary purpose of a harden and temper line is to get the most performance out of a specific material chemistry: a chemistry that is custom engineered to a specific application and will deliver the qualities most necessary for API tubing and casing products. Numerous manufacturing shortcomings have led to recent advancements in the technology of a manufacturing process that has remained relatively stagnant for a long period of time. With that said, what are the characteristics of a modern quench and temper system used for oil country applications?

- The ability to process both welded and seamless tubular products with equal quality levels.
- The ability to process a wide range of steel metallurgy without compromising quality or productivity. Dual phase, AHSS – advanced high strength steel, and high alloy steels containing chrome.
- The ability to process less alloyed steels to high mechanical properties resulting in savings in the purchase of steel.
- The ability to produce on a singular line, a wider range of product diameters and wall thicknesses to match the upstream developments in tube producing lines.
- The ability to overcome traditional quenching issues like quench cracking, high residual stress, straightness, and metallurgical transformation (Martensite) without compromising productivity.
- The ability to model products prior to processing and to transfer that information into the control system operating parameters to streamline setup from batch to batch.
- The ability to store and repeat successful operating setups from a custom developed menu.
- The flexibility to process standard and short batches while avoiding idle periods using the process recipes to facilitate quick change-over without loss of yield.

Figure 1: *Bar and seamless pipe quench and temper system designed for lean manufacturing*

Harden and temper lines currently employ a vast array of different technologies and practices, from gas to induction furnaces on the heating side to nozzle versus precision quenches on the hardening application. The following discussion will detail various heating and cooling methods and the benefits of each, as well as describe some basics of the process. Most importantly, how do recent advancements in analytical modelling, coupled with

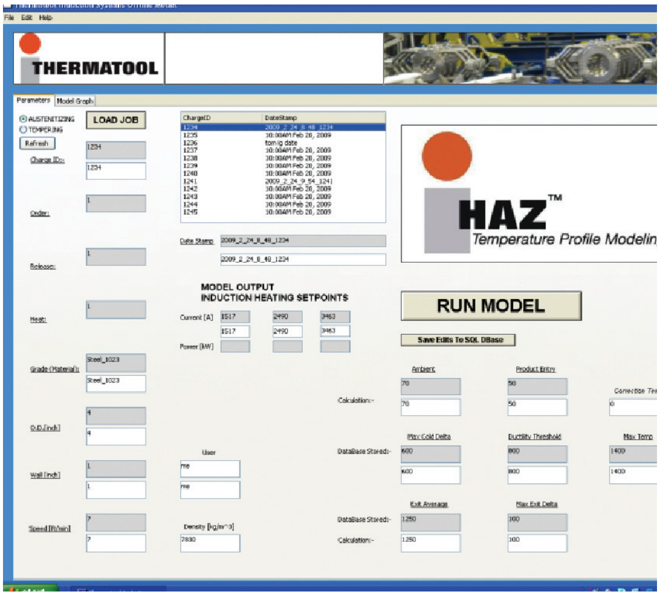

Figure 2: *PC data input and batch retrieval*

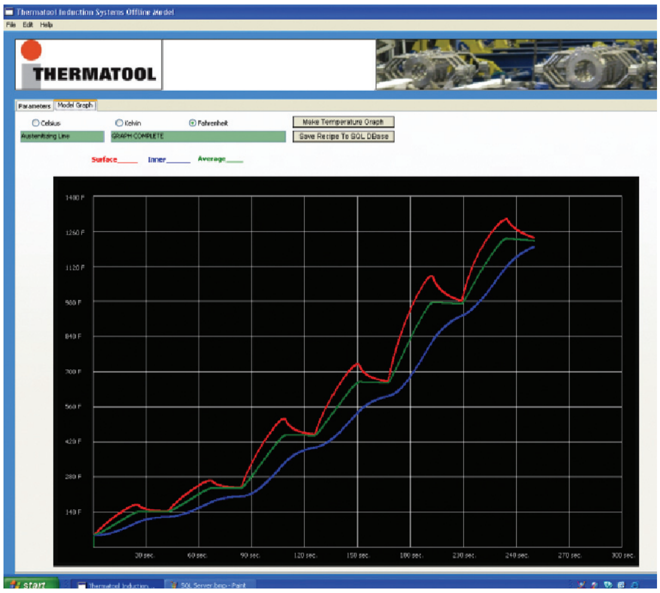

Figure 3: *Modelled temperature profile for bar*

process control, equipment design and application, achieve the characteristics listed earlier?

Austenitising, the first step in the metallurgical transformation, involves imparting heat to a particular product, getting it up to temperature as quickly as possible. Soak isn't necessary, but is sometimes used as a means to guarantee that the product has reached a certain temperature through its core. In vintage quench and temper lines, this was accomplished through either a limited number of very large induction power supplies with just a few coils, or a gas furnace, or the combination of both. Problems associated with this are a rapid heating which produces grain growth and the introduction of thermal stresses, insufficient through wall heating, or an enlarged gas furnace footprint. To overcome these shortcomings, induction heating systems have been engineered, sized, and laid out in a way to control the heating process. Controlled heating is the ability to induce the maximum amount of thermal heating into a product without creating issues of straightness due to thermal shock, wide disparity in grain structure, or excessive scale formation on the surface. Products entering a heat treat line can come with many stresses previously induced from upstream processing such as rotary straightening. In addition, wall thickness variations in seamless tube can present a challenge to even heating with induction and gas furnace technology. When these stresses are released they result in a loss of straightness in the product and loss of productivity. The primary solutions to this problem are to slow down the line or to invoke a post-hot straightening station. Aggravating this problem, many lines are designed with a minimum number of coils and a minimum number of large power supplies, which result in a 'high density' of power being induced in a distance that is too short. The controlled, or gentle, heating design incorporates more power supplies creating more zones of heating control. This allows for the power density to be reduced in the leading zones and coil sets as well as more flexibility in processing speed. Final zone power is increased to compensate for the shift in the heating curve with the total power required remaining the same. The ability to manipulate the heating curve between multiple power supplies also provides the capacity to match inverter power in a manner which does not overheat the surface or under heat the ID of the product. This type of heat control must be repeatable and adhere to required TTT curves. The time and temperature data must be generated according to the desired resultant material properties. These calculations can be accomplished using modelling software which will transfer the time and temperature information to the power supply (see figures 2 and 3 for model examples).

The ability to model and alter power distribution through the application of more power supplies for zone control is new and results in better process control and

Table 1: *Advantages and disadvantages inherent in different austenitising methods*

Aust. method	Advantages	Disadvantages	Ideal for
Gas furnace	- Confidence of through wall heating (soak) - Affordable run-time utilities	- Slow response time - Long start-up delays - Slow line-changeover - Loss of utilities during production delays - High installation cost - Lost efficiency with extra soak time - Long line length	- Single production customers - Large batch order processing - Locations with cheap gas utilities - Companies with consistent predictable production schedules
Induction furnaces	- Fast reaction time - High line speeds - Instant temperature variability - Precise heating - Low installation cost - Short line length	- Electrical utility cost - Soak potential reduced - Temperature of product less stable throughout process	- Short batch producers - Producers interested in maximum line variability - Locations with cheap electrical utilities - Lean manufacturing
Induction pre-heat gas soak	- Adaptability for multiple products - Confidence of soak	- Floorspace considerations	- Large production centres with varying product schedules - High speed and high flexibility

product quality. The combination of on-line analytical models downloading results directly to the process control computer has created a new era in heating before hardening technology. A modern quench and temper line will no longer rely solely on limited data from external temperature monitors, to control heating power. Additionally, the controlled gentle heating system is designed with sufficient power and time under coil to effectively produce high strength metallurgy with elements such as chrome which require complete heating during austenitising to come into solution with the other elements prior to the quenching.

These controlled heating software model techniques were originally developed for the forging billet heating industry under the name iHAZ. During the heating of solid materials, if time is not allotted to allow temperature equalisation via conduction within the piece, localised thermal expansion can cause internal cracking. The cracking can take form as catastrophic failure or hard to notice micro-cracks. In the case of forge billets, by increasing the temperature of the material in controlled waves using the iHAZ predictive models, conduction within the billet can catch up to the rapid induction heating of its surface. With the adoption of the iHAZ software, billet heating can be performed rapidly without the risk of cracking or shell separation. Ultimately, the controlled heating software can help tubular product and billet producers reach maximum production speeds with the greatest control over material microstructure.

As mentioned previously, older technologies inherently do not provide individual coil control and deliver only one heating profile for all wall thicknesses and speeds. Modular power supplies and multiple coils accomplish 'gentle heating' utilising the model output. Furthermore, process recipes which optimise the heating profile through wall or surface to core are stored for later use. Table 1 details some of the advantages and disadvantages inherent in different austenitising methods.

Quench hardening, the next step in the hardening and tempering process, has employed the least amount of control and development in past years. Recently, much emphasis has been placed on quenching to refine the

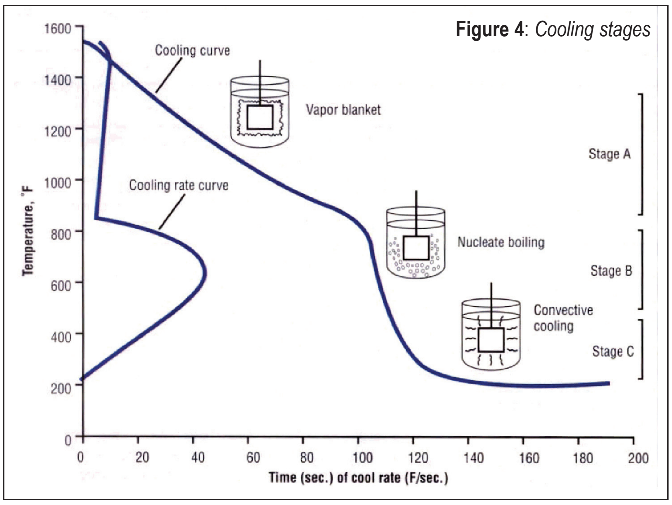

Figure 4: *Cooling stages*

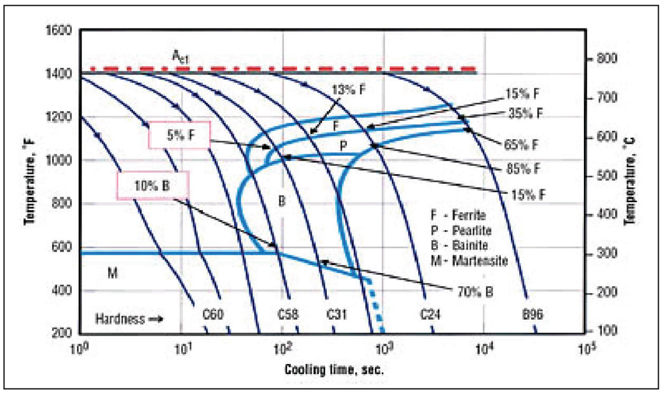

Figure 5: *Continuous cooling transformation (CCT) diagram for AISI type 15B41 steel (0.42%C, 1.61% Mn, 0.29% Si, 0.006% P, 0.019% S, 0.004% B), grain size: 7-8 [8]*

process and dictate martensite creation through controlled cooling. Controlled cooling (step down quenching) is the ability to process at 'line speed' a diverse range of tubing and casing as well as differing metallurgies. This requires the ability to control the 'severity' of the quenching process based upon characteristics of the product being produced without allowing line speeds to dictate the process. The variables in quenching are: product diameter, wall thickness, mass flow rate, and desired metallurgy. In the process of austenitising the heating mass is many times used as the single parameter for sizing power supplies and ultimately line speeds. This single parameter of design is insufficient when considering the quench design. High strength steels often have metallurgical elements (high carbon, alloys) which make them susceptible to quench cracking requiring a gentle, less severe quench approach. Products that have a lean metallurgy with low alloy and a very short quench window require an aggressive, severe quenching system designed to meet the demands of both situations requires that mass or cooling capacity of volume not be the predominant design criteria for control. These factors require a precision quenching system which utilises a delivery system that can allow for high pressure quenching, and high flow and yet maintain the ability to be programmable.

New types of quenches, such as precision slot quenching rings, have evolved the concept of quenching from a 'static' high volume approach to a programmable system in which many elements of processing can be translated into line set-up, recorded and stored for future process runs. This type of system utilises variable speed pumps to establish control of pressure, volume and the velocity of the water at the point of contact with the work piece. In turn, these quench parameters can be adjusted to that which best suits the product being processed. By having an uninterrupted conical flow of water around the product through the precision quench ring, straightness is also optimised. The precision quench system also allows for zone control of quench ring sets to be programmable to the product characteristics both in velocity (ie severity of quench) and in time through quench to match not alter optimum line speeds.

To fully understand the criteria necessary for the design of a modern precision quench, we must first understand the stages of heat removal and how to accelerate the process.

There are three stages of heat removal associated with quenching in liquids, commonly referred to as stages A, B and C. Stage A, the vapour blanket stage, is the first step in which a vapour blanket forms around the quenched metal. Heat transfer from part to quenchant in stage A is reduced due to the poor thermal conductivity of the vapour blanket. Stage B is the nucleate boiling stage, in which the vapour blanket collapses and the heat is rapidly transferred from the part to quenchant. It is in this stage that the quenchant is in direct contact with the part and the rate of cooling maximised. The third stage is the convective cooling stage, beginning when the temperature of the part has cooled below the boiling temperature of the quenchant. Heat transfer in stage three is reduced and is controlled primarily by the viscosity of the quenchant.

It can be readily seen from figure 4 that minimising the vapour blanket so that the nucleate boiling stage can begin as soon as possible is desirable. In batch processing systems, the extension of the nucleic boiling stage is achieved through aggressive aggravation of the quenchant within the quenching tank.

Precision slot quench rings provide a means to aggravate the quenching process and collapse the vapour blanket in a continual processes application like that used for heat treating of tubular products. The slot quench ring is engineered to ensure the quenchant has sufficient kinetic energy to penetrate the vapour blanket while maintaining relatively small surface to volume ratio, ensuring maximum contact area between the quenchant and the part. By minimising the vapour blanket phase, the slot quench rings allow the nucleate boiling phase to begin very quickly. It is in this stage that the maximum amount of energy is transferred to the water from the part.

This highly effective transfer permits quench time and quenchant mass flow to be reduced, ultimately increasing the heat transfer coefficient between the quenchant and the product. Other quench systems rely heavily on very large mass flow rates to achieve cooling. Precision quenching systems rely as much on the geometry of the spray as the volume and pressure of the quenchant. Extensive quenching research is being performed to best model the precision quenching system given the multiple variables associated with the method. The quench tests involve a theoretical analysis of the precision slot quench system, accompanied by validation tests to authenticate the models. Since the precision slot quench system utilises individual quenching rings, additional optimisation can be accomplished via careful spacing of the multiple quenching rings. Precise spacing helps the producer carefully control the rate of cooling using both the aggressive convection on the surface, as well as the time dependent conduction of the product in between rings. Precision quench system variables other than ring spacing include: flow, quenchant temperature, pressure, water impingent angle, number of rings, ring/product diameter ratios, and quenchant composition. Because quenching requires cooling through a narrow process window, adjusting these variables with the aid of an advanced model help the operator ensure that his process produces an acceptable result.

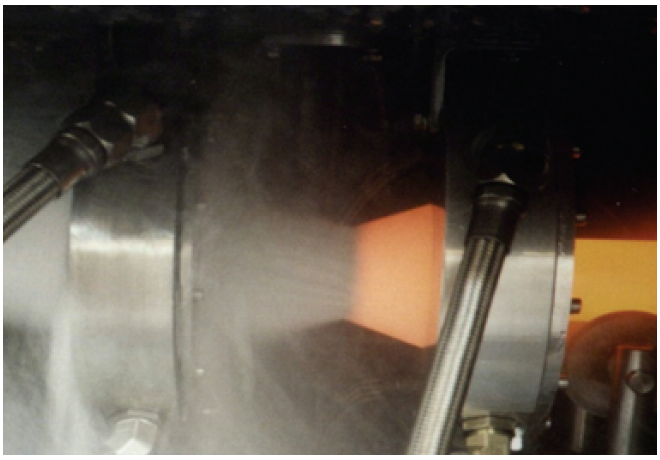

Figure 6: *Precision slot quench rings in operation*

Additionally, this narrow process window varies depending not only on the chemical composition of the materials being quenched but also with temperature as the process proceeds. Instead of using the steady-state time/temperature curve to model quenching accurately, it is necessary to use a continuous cooling transformation (CCT) curve or diagram, which better describes the transformations even as material properties change mid-process. Having the tools

Aust. Method	Advantages	Disadvantages	Ideal for
Gas furnace	- Confidence of through wall heating (soak) - Affordable run-time utilities	- Slow response time - Long start-up delays - Slow line-changeover - Loss of utilities during production delays - High installation cost - Lost efficiency with extra soak time - Long line length	- Single production customers - Large batch order processing - Locations with cheap gas utilities - Companies with consistent predictable production schedules
Induction furnaces	- Fast reaction time - High line speeds - Instant temperature variability - Precise heating - Low installation cost - Short line length	- Electrical utility cost - Soak potential reduced - Temperature of product less stable throughout process	- Short batch producers - Producers interested in maximum line variability - Locations with cheap electrical utilities - Lean manufacturing
Induction pre-heat gas soak	- Adaptability for multiple products - Confidence of soak	- Floorspace considerations	- Large production centers with varying product schedules - High speed and high flexibility

to modify the quench within tight tolerances allows the best opportunity to match the cooling curves for each particular chemical composition (figure 5).

Modelling is simplified in part because of the axial symmetry of the process. This axial symmetry improves straightness and delivers a consistent hardness profile due to uniform contact and a higher depth of penetration.

In contrast to other nozzle type quenching systems, the most modern precision slot quenches employ a recipe creation and retrieval control system. Once a product process is set up and validated using this system, those process parameters can be retrieved for easy system set up when running the product at a later date.

The final hurdle that older quench types fail to clear is the maintainability problem. Scale creation is a by-product of the harden and temper process. Dealing with this scale is crucial for barrel or tangential quenches to avoid clogging issues. The continuous slot design of the slot quench ring severely reduces clogging. Scale that would have previously obstructed the fine orifice of a barrel or tangential spray nozzle passes freely through the slot quench ring. In tests, obstructions as large as a quarter were found to have minimal impact on the quality and consistency of the precision slot quench ring spray.

The quench systems below are a cross section of older and newer technologies available today. While the methods for tempering match those for austenitising, the purpose is vastly different. Unlike austenitising, it is not the peak temperature that matters as much as the time at temperature. The goal of the post quench reheat is to increase ductility of the product.

As-quenched hardened steels are so brittle that even slight impacts may cause fracture. Tempering is a heat treatment that reduces the brittleness of a material without significantly lowering its hardness and strength. All hardened steels must be tempered before use.

Different materials call for different tempering times and temperatures. The tempering challenge is to maintain a flexibility and efficiency for all types of time/temperature profiles while still controlling the process. Induction allows that degree of flexibility, especially as one considers the adaptability offered through variable inductance power supplies.

Through the use of multiple power supplies and coils with or without a gas furnace, flexibility can be added to a process that allows for tempering of various diameters and wall thickness as well as batch sizes. However, soak time is vital and gas furnaces offer a stability that is unmatched for larger product sizes and production requirements. Like austenitising, those interested in the most efficient and economical lines should look at the marriage of induction pre-heat systems coupled with gas soak furnaces. These so-called hybrid lines offer benefits that are derived from both types of heating. Induction power offers reduced scale, rapid temperature achievement, small footprints, and no

Figure 7: *Multiple modular induction*

environmental considerations, while gas furnaces operate on an economical scale due to the natural gas and the ability to hold products for extended periods in a footprint that is advantages to soak.

The ability to combine these two methods can create a very versatile line capable of both standard and short batches to maximise the line's utilisation. Possessing the ability to control the harden and temper process while ensuring required metallurgical properties is paramount to API tubing and casing producers today.

As competition abounds globally, one must have the ability to differentiate their products to potential end users. This could manifest itself in the creation of proprietary grades, or even the ability to produce live processing data from beginning to end of the process. Doing that requires an in depth research of the tools available today and the pros and cons of each.

The industry has long been constrained by preconceived notions that technology in hardening and tempering is set and little was left to be improved upon. Contrary to that assessment, there has been a period of tremendous development in software modelling and technical advancements in processing for other industries (ie automotive, forging, etc). These developments opened a window of opportunity for an application of this to an industry which had changed dramatically due to the high cost of steel and a demand for higher performance energy related tubular products.

When considering the benefits of process control, repeatability, enhanced straightness and metallurgy that modern quench and temper lines offer, competition demands that these features be integral. Acceptance of a limited range quench and temper process with corresponding expectations based upon old processing beliefs or the realities of a static design are no longer options in today's economy.

Thermatool Corporation
Email: info@ttool.com Website: www.thermatool.com

Thermatool IHWT Ltd
Email: info@ihwtech.co.uk Website: www.inductotherm-hwt.co.uk