

## Introduction to Integrated Heat Treating Solutions, LLC

# Everything Matters to Reach ASM HTS's Vision 2020 Goals

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### Abstract

In 1999, ASM's Heat Treating Society set forth a view of what the ideal future for the heat treating industry would be by the year 2020. Among the goals is to ***"Achieve zero distortion and maximum uniformity in heat treated parts."***

Since heat treating is a crosscutting technology, it affects, and is affected by, many aspects of part design and manufacture. All the parties in the lean manufacturing value chain, including the heat treater, must realize that ***"everything matters"*** when trying to eliminate waste. Lean concurrent engineering teams must collaborate to integrate their innovations, they develop seamlessly, into the methods and equipment they use to make and to market their products.

The author will review the 1999 ideals set forth in Vision 2020 and how far we have come as of 2017. The author combines his dual perspectives performing traditional commercial heat treating for over 35 years for over 1,200 different customers, as well as his work with many lean part making customers and "heat treat waste-fighting" colleagues commercializing advanced heat treat quenching methods and equipment since 1997.

- Achieve zero distortion and maximum uniformity in heat treated parts
- Return 25% on assets
- Create 10-year partnerships with customers.

### What can Heat Treaters do to reach Vision 2020 goals?

In the ASM Vision 2020 goals are two manufacturing goals that are foundational "lean principles":

***"Reduce [heat treating] production costs by 75%"*** and

***"Achieve zero distortion and maximum uniformity in heat treated parts."***

The adoption of lean manufacturing practices are the foundation for making "better" products or offering "better" services at a total lower cost. Lean driven activities seek to eliminate as much "Muda" or "waste" as possible in each step of manufacture, while at the same time adding as much "value" as possible throughout the manufacturing stream. Lean innovations come in three "intensities": incremental innovation, jump innovations and disruptive innovations.

**"Muda (無駄)** is a **Japanese** word meaning "futility; uselessness; wastefulness," and is a key concept in the Toyota Production System (TPS) as one of the three types of deviation from optimal allocation of resources (the others being **mura** and **muri**)."  
(*Wikipedia*)

Since heat treat metallurgy is a crosscutting technology, it affects, and is affected by, most aspects of lean part design and manufacture. All the parties in the lean manufacturing value chain, including the heat treater, must realize that ***"everything matters,"*** when trying to achieve the desired form, fit and function, for a heat treated part and at the same time achieve the lowest total cost of manufacture and sale. For value engineers to address the three enemies of **Lean**: **Muda** (waste), **Muri** (overburden) and **Mura** (unevenness), all parties along the value-adding stream must embrace the three types of innovations, incremental, jump and especially disruptive to realize "stretch goals" such as those set forth in Vision 2020.

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### Introduction:

## Everything Matters to Reach ASM HTS's Vision 2020 Goals

Beginning in 1994, the R+D Committee polled various ASM members and industry executives to identify the collective view of an ideal future for a profitable, high quality, environmentally sound and sustainable heat treating industry. It is now 2017, almost 18 years since the ASM Heat Treating Society's R+D Committee published its "Vision 2020" Goals that set forth the following performance targets:

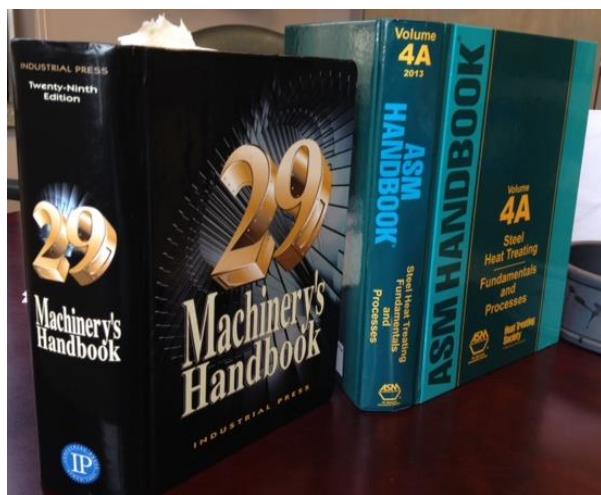
- Reduce energy consumption by 80%
- Improve insulation
- Achieve zero emissions
- Reduce production costs by 75%
- Increase furnace life ten-fold
- Reduce the price of furnaces by 50%

*can only be done with concurrent engineering along the value chain.*

The first step to eliminate the Muda in the heat treatment of metal parts, the heat treating processes must be *integrated* as a “full partner” in all dimensions of the lean manufacturing value chain. Optimizing the controlled “heating + cooling” processes (in the optimal heat treating equipment) requires *full integration* of heat treatments from the very beginning of the lean part design process, including an optimal alloy selection for the “intended” heat treating processes for the specific end-use. All the manufacturing partners can then collaboratively address the root causes for the Muda that lies “upstream” or “downstream” from the actual heat treating processes, especially the waste created in the hardening process from unpredictable part distortion from the quenching process.

Blacksmiths were arguably the first “lean integrated” heat treaters. One person, the blacksmith, selected the raw material, designed the part at the forge, and hardened the part at the forge. Usually employing only water or brine quenchants getting the desired mechanical properties, and then straightening the part while tempering.

For mass production of hardened parts, this integrated, single-person design and manufacture of hardened parts is not scalable. So the part design, the material manufacture and the alloy selection, as well as the forging and the hardening processes, are usually all done by separate entities each with their own area of expertise. The result is our modern heat treating industry has become somewhat fragmented and removed from the main part forging and machining operations. Without the heat treat metallurgy knowledge being fully integrated into the upstream part design and manufacturing value chain, the heat treating process is often not as lean as it could be, and there is also waste caused downstream of heat treating.



*“Lean Teams” must consider a lot of machining, casting, forging and heat treating knowledge to eliminate Muda and optimize the part design and manufacturing processes. This*

Whether the heat treat industry Muda is rooted inside our own heat treat plants or elsewhere in the part making value chain, the goal of lean is the same – to eliminate waste everywhere it is hiding and to add maximum value for the least amount of total cost. From part design to finished part packaging and shipment, each “customer” along the value chain wants the following from their lean programs:

- I. Better products;
- II. Faster service; and
- III. Lower overall cost.

Offering the customer a better product or service *and* at a better value is what Bell Laboratories, Thomas Edison, and other prolific innovators always tried to achieve. Consumers vote with their pocketbook and buy the best *perceived* value. Former GE CEO, Jack Welch, once said, “An organization’s ability to learn, and to translate that learning into action, is the ultimate competitive advantage.” Businesses compete with their strategic efficiencies gained through their lean programs.

Every heat treated part end-user, the ultimate customer for the part, wants the same things from their heat treat processes and equipment:

- I. Better mechanical and physical properties from “leaner” or less expensive alloys;
- II. Net shape or near net shape parts after heat treating that need no straightening or grinding after heat treating; or heat treat with “predictable” distortion so that pre-heat treated parts can be machined “off-spec” then predictably “morph to spec” after hardening;
- III. Higher energy efficiency and the lowest possible environmental impact (lower CO<sub>2</sub> emissions, no hazardous quench oils, or other chemicals, cleaner parts, shortening or elimination of long batch carburizing cycles, etc.); and
- IV. Faster processing and lower work in process inventories in the heat treat department (single-part flow); or no heat treating department with in-line heat treating within the part machining cell or incorporated directly into the hot forging operation (DFIQ).

Although every heat treating customer wants the same things from their heat treater, there is often times no direct contact between the heat treater and lean team members upstream and downstream that will help determine what is wanted and how to give it to them. Unfortunately, the part designers, the part makers or end-users in many cases simply do not consider the heat treater as a “full partner” in the development of their lean part designs or initiate any integration into the lean part manufacturing value chain until there is a “heat treat problem.” All members of the part design and manufacturing value chain must recognize heat treating as the critical link in the chain it really is. Although heat treating costs are only

5% to 10% of total part costs, improper heat treatment can lead to rework, additional cost, and/or scrap ... all of which can greatly exceed the 5-10% of direct cost that heat treating represents.

The material specification may be set in the part design before the part machinist even begins to make the part that will be sent to the heat treater for hardening. In fact many times the heat treaters will process parts that they do not even know of the part's needed final form, fit or function until there is a "problem" with the part.

For the better part of the 20<sup>th</sup> century, many commercial heat treaters used their own mix of "art and science" when hardening various parts made of different alloys of steel. The development of heat treating practice is therefore fragmented between the various "heat treat process developers" and the part designers and the part makers. Straightening, flattening and fixturing must also be done on many parts to manage distortion on various geometry parts caused by non-uniform quench cooling (film boiling) that could be avoided with the proper material optimized for the intended quench process.

Although steel making has gotten much more clean and consistent, there are still variations in steel chemistries from different batches of steel that heat treaters must adjust their processes to achieve the desired mechanical properties. Since the steps for "tweaking" a process are fragmented they are often not fully documented, even in the "tweaker's" own organization. Our tribe's "tribal knowledge" is rarely documented in any industry. Even when documented, the tribal knowledge is not shared between different tribes of heat treaters and unfortunately their part making customers. These techniques, often developed by trial and error over many years, are a real competitive advantage to increase part mechanical properties, reduce distortion and reduce grinding or straightening costs.

Even when "new" heat treat processing technologies are clearly shown to have moved from disruptive to enabling of major benefits to the part making value stream, the industry fragmentation provides no clear path for quickly promulgating the new methods, in the new equipment, on the new designs using the optimal new materials.

Sunk costs in existing equipment also slow the shift to new equipment for any new technologies. Compounding the fragmentation of processing knowledge is the high cost of readily available new heat treating equipment to execute the lean enabling heat treating processes. While open fire furnaces, controlled atmosphere furnaces, vacuum furnaces, induction heating equipment, or salt bath furnaces, may all be capable of attaining the needed heating temperatures in the part, the various types of equipment cannot be used interchangeably for specific part applications. Likewise, the optimal quench cooling after austenitizing usually requires specialized quenching systems integrated with specific quench medias – an oil, water/polymer, air or inert gas, molten salt, or

intensive water quench are not really interchangeable with different quenching systems.

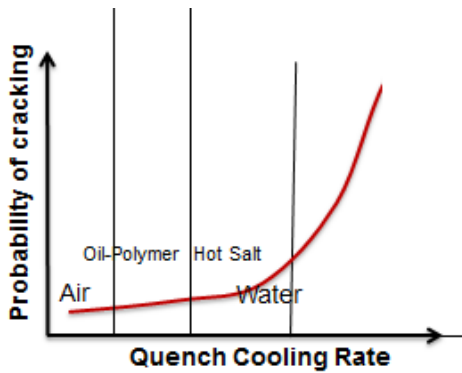
Sunk costs in existing equipment slow the shift to new equipment for any new technology, but in heat treatment there is the double whammy – adopt a new method AND adopt unproven new equipment?! The aversion to risk inherent with trying "something new and better" may serve as a barrier to even incremental innovations. It is even more difficult for a disruptive innovation, such as intensive water quenching of steel to be adopted, especially if it is not even mentioned in the heat treating handbooks until 2014.

Many captive heat treaters that heat treat the products they manufacture, and the commercial heat treaters that have long term relationships with their customers, are doing "cookbook" heat treating developed years ago for their customers' parts. These "time tested" processes are usually engrained in their part specifications making "translating new learning into action" impossible. Tried and true processes and equipment usually prevail unless the equipment dies or the raw materials are simply unavailable – e.g., cyanide salt bath carburizing. Translating new learning into action in the aerospace industry, where parts were flight certified with specific approved heat treating processes and equipment, is almost impossible until the whole airplane is redesigned.

Simply put, no one entity, the part designer, the steel maker (the forger or caster), or the heat treater, has *integrated* the "whole book of heat treat knowledge" needed to design and manufacture new hardened parts in the leanest manner for the best part at the lowest total cost of manufacture. Only working collectively can they hope to optimize the value engineering needed to make the best heat treated part at the lowest total cost of manufacture.

To meet Vision 2020 goals we must integrate all flavors of innovation: incremental, leap and even disruptive. Process models are driving disruptive innovations that are counter-intuitive to our thinking outside the current practice. Since 1999, more powerful FEA-based computer modeling programs, some of them three dimensional, for aiding in optimal steel alloy selection, optimizing casting and forging processes, as well as for optimizing heat treating processes, have boosted our understanding of heat treat metallurgy. The advent of a wider use of Computational Fluid Dynamics (CFD) and thermal process models have aided our understanding of the traditional as well as advanced heat treating quenching processes. All this modeling has been enabled by less expensive, yet more powerful, computers.

Likewise, new, more robust affordable computerized heat treat process control systems, with real time data logging, have helped move our industry forward to the Vision 2020 goals for higher quality, more consistent hardened parts, at a total lower cost of manufacture.



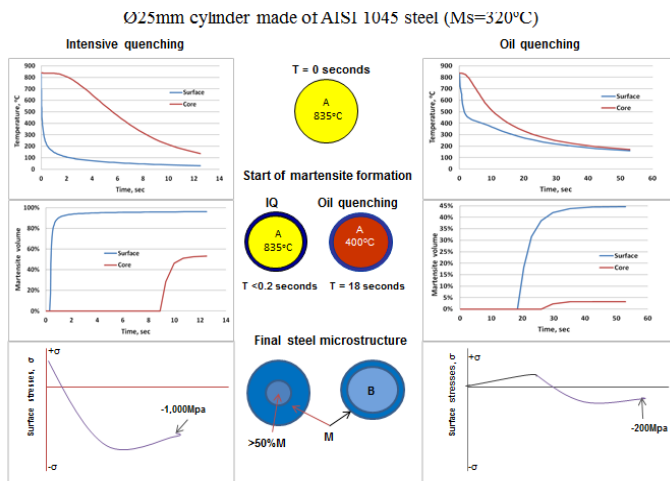
**Traditional Heat Treat Theory: “Quench Cooling Rate vs. Probability of Distortion” Part cracking increases the faster the quench cooling rate.**

We now understand the role that compressive surface stresses play in controlling part distortion and enhancing part properties in heat treating. We understand by **uniformly creating** in-situ or “current” compressive stresses in the part shell from the very beginning of the quench, that the relationship between the rate of quench cooling and the probability of part distortion is not linear, but a bell-shaped curve.

Since compressive surface stresses are of no use if they are disturbed (removed) after hardening to correct the unpredictable part distortion caused by a non-uniform quenching process, the heat treater must also control distortion. The understanding that the root cause of most part distortion is the “non-uniformity” of quench cooling and not the speed of the quench cooling rate, has opened the door for getting more strength and ductility from parts, using leaner, less expensive alloys, with an intensive water quench.

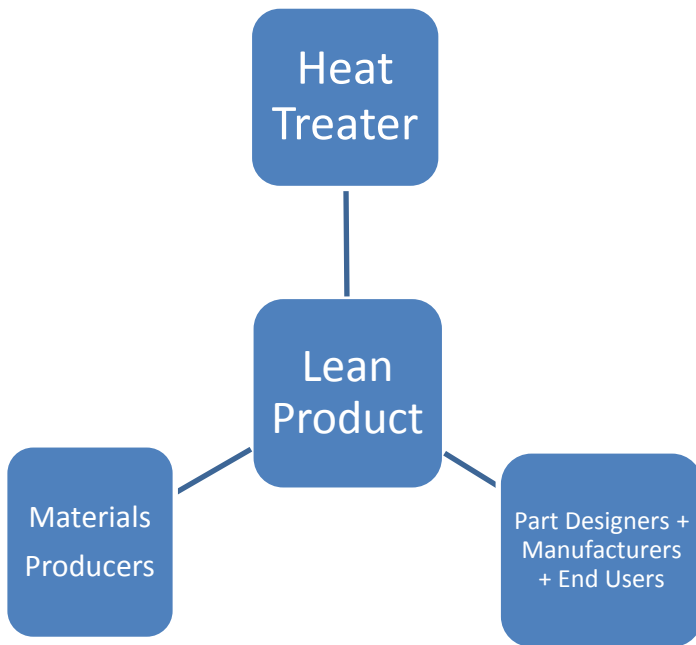
More uniform gas quenching, uniform molten salt quenching, and “Uniform + Intensive” water quenching have all made consistent, “predictable distortion” a reality for many quench and tempered parts. With quench cooling that is so consistently uniform and predictable; the part before hardening can be machined in a “distort to fit” shape that becomes the desired final shape after the uniform quenching. This moves the heat treater one step closer to being a full partner in the lean manufacturing chain.

During an intensive water quench, uniform compressive surface stresses in the martensitic shell can also hold the hot part core “like a die” that reduces part distortion and prevents part cracking. A “uniform and intensive” quench can also provide a finer grain structure, enhancing part hardness, ductility and stress state for a given alloy of martensitic steel. This combination allows part designers to use leaner (less expensive) alloys of steel yet still achieve the same mechanical properties of a higher alloy of steel that is hardened with a traditional “non-intensive” quench using oil or polymer/water quenchants. The intensive quench also provides for enhanced residual compressive surface stresses for longer part fatigue life. Since the “predictable distortion” from a uniform and intensive quench makes the compressive surface stress layer uniform, both the disruption of the stress layer as well as the amount of final grinding is minimized. Maintaining the uniform distribution of residual compressive surface stresses during final part grinding also keeps part movement in post-heat treat grinding to a manageable level.



**Dynamics of Temperature, Structural and Stress Conditions In 1045 Steel Parts During Oil and Intensive Water Quenching (DANTE modeling data and x-ray diffraction data)**

## The 3-Dimensions of Integrating Heat Treating Processes and Equipment for Lean Manufacturing of Heat Treated Parts and Moving Closer to Vision 2020 Goals.



*The Lean Team for making hardened parts needs to include all the parties that are adding value to the part. To eliminate “waste” you must include the heat treater to choose the optimal hardening alloy for the “intended quench” and to achieve the optimal part hardness, ductility and stress state for a given alloy, as well as have more predictable distortion and optimal grain refinement all for the particular end-use.*

**I. The First of the Three Dimensions of Lean Integrated Heat Treating practice is to look both “upstream” and “downstream” from each of the heat treating process to be used, to eliminate Muda from the pre-heat treating design choices as well as to be as lean as possible downstream of part heat treating, especially after the quench and temper processes are done.**

Therefore, to eliminate heat treating waste, the optimal heat treating processes and equipment used to harden the part must be fully integrated into the lean manufacturing value stream, and *in the proper order of part processing*. The part designer and raw material provider must consider the intended heat treating processes that will be required to obtain the required part form, fit and function at the lowest total cost of manufacture. The least expensive alloy that can attain the needed mechanical properties may not be the optimal alloy for the anticipated oil or water/polymer quench process. Conversely, a higher alloy, more expensive steel may not be needed to meet the mechanical properties if an optimal

“uniform and intensive” water quench is used to extract finer grains and optimize the hardness, ductility and compressive stress state in the part.



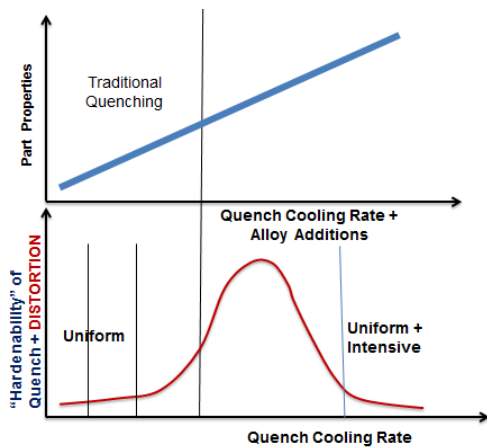
*Properly hardened “block” is not necessarily the properly hardened “part” carved from the block after hardening. To eliminate waste the designer should have considered machining the part from the unhardened block of steel then hardening the machined part with a hot salt quench (martemper) that controls distortion and at the same time gets the desired mechanical properties in the part.*

The selection of the optimal heat treating process for a new part design cannot be done from the individual silos of expertise that are used to manufacture the part. To make better heat treated parts at a total lower cost of manufacture, the heat treating solutions must be integrated into the design and material selection processes as well as all the value-added processing steps (in the proper order of “flow”) that are baked into the part specifications.

**II. The Second Dimension of integrated heat treating practice is to begin with an optimal part design (shape and mass) that uses the “Optimal Hardening” material for the “Intended Quench” (“OHIQ” Materials).**

Clean, high quality, optimal hardening steel for the “intended quench” when hardened in the proper lean integrated heat treating equipment, will reliably achieve the optimal part hardness, ductility and stress state, for a long part service life in its intended end-use. The optimal hardening steels combined with the optimal heating and quenching processes will give the part designer the desired form, fit and part function with the desired mechanical properties, all at a total lower cost of manufacture.

Lean-integrated heat treating also reduces the risks of part failure by addressing the expected failure modes or “unintended” uses of the part, as well as attaining the other “collateral characteristics” desired for the hardened part (e.g., low distortion, lightness, corrosion resistance, pitting or galling resistance, impact and wear resistance, heat-cool cycle fatigue resistance, field reparability, etc.).



*Part design must match the material selection to the optimal hardening steel for the “intended quench” – To achieve the desired mechanical properties and long part service life, the part designer must provide enough “hardenability” from the steel alloy, OR get the hardness to a depth with a more intensive quench on leaner alloy steel.*

**III. The Third of the Three Dimensions of Lean Integrated Heat Treating practice is to *integrate* the heat treating processes and equipment with all the other lean value-add processes, in the proper order of manufacture:**

**Optimal part design for the intended, and “collateral” end-uses, using an**

**Optimal Hardening alloy of material for the “Intended Quench” +**

**Matched with the optimal heating methods and the optimal “uniform” gas or hot salt quench (single phase cooling), or “uniform and intensive” water-based quench cooling processes (with no film boiling), interrupted at the optimal time (for final core cooling by uniform conduction through the cold shell);**

**All performed in “lean + green” equipment optimized for part production flow, that**

**Develops the optimal microstructure for a given alloy of material, for**

**Optimal hardness, ductility and an optimal compressive surface stress state.**

Full integration of the hardening processes and equipment with the upstream part design, and alloy selection, as well as the other downstream “value-additions” will enable the following benefits for the part manufacturers and their end-users:

A. Hardened parts with optimized form fit and function for the part end-use, including optimal mechanical properties,

optimal microstructure, including residual compressive stress state, from finer grains for a given alloy of material;

B. Parts made from the least expensive wrought, cast or forged alloy of metal (steel, ductile iron or non-ferrous material) that will fully develop all properties the given alloy of steel or ductile iron can possibly deliver;

C. Consistently low, predictable part distortion, that enables net shape or near net shape parts after hardening; parts that do not require risky cold straightening, flattening or costly grinding after hardening. Parts that can actually be rough machined to “distort to fit” in the intended part envelope after “Uniform” or “Uniform and Intensive” quench and temper.

D. Higher power density parts that provide for the longest service life for the part end-user at the lowest total cost of manufacture;

E. Lean and green heat treating processes that can be readily integrated into the part making processes for in-line, single-part or batch processing matched to the lean part manufacturing flow.

There are five Case Studies in the Appendix to this paper. Each Case Study demonstrates a practical application of integrating all three dimensions of three dimensional heat treatment to particular products that enabled the above benefits for lean part manufacture at a lower total cost of manufacture for the end-user.

## CONCLUSION:

For the heat treating industry to achieve the Vision 2020 goals set forth for us so long ago, we must collaborate with all the other members in the lean part making value chain. Since heat treating is a crosscutting technology, it affects, and is affected by, many aspects of part design, materials and manufacturing steps. All the parties in the lean manufacturing value chain, including the heat treater, must realize that “*everything matters*” when doing value engineering on heat treated parts.

Everything matters in all facets of lean manufacturing. Optimizing the heat treat process is no exception. To eliminate Muda, Muri and Mura everyone at each step of part design and manufacture, including the heat treater, must collaborate to eliminate waste and to realize the benefits of lean for all parties in the value stream. Integration and optimization of the many crosscutting dimensions of heat treating processes, as well as the optimal equipment and material handling, starts with making the heat treater a full partner in the lean manufacturing value stream.

This lean integration with others upstream and downstream of heat treating is the only way heat treaters can eliminate the pains of distortion and non-uniform properties, as well as

lower heat treating costs, for not only our customers, but our customers' customer.

Heat treating can only be fully optimized for the part end-user's specific applications when done with the optimal heating and cooling processes; using the optimal heat treating equipment; on optimally designed parts, made of high quality materials that have an optimal response from the intended heat treatments. A consistently longer wearing part with the highest power density, made at a total lower cost, is the product of integrating optimal heat treating solutions with lean part manufacture.

The order of processing is also very important. To get it all right, the part making value stream cannot be navigated from our individual silos of expertise, but concurrently engineered with innovations brought to each field of practice. Each lean concurrent engineering team must collaborate to eliminate waste and to integrate fully their innovations they develop seamlessly into the production methods and equipment to produce better products or to provide better services that enable all parties to realize a competitive advantage.

Everybody wins when lean-driven innovators in the part manufacturing value chain collaborate, including the heat treater, and Vision 2020 comes closer to reality.

### **Acknowledgements:**

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A special thank you to the late Professor John (Jack) Wallace, Dean of the Department of Metallurgical Engineering at Case Western Reserve University. Jack was like many other metallurgists who initially did not believe intensive water quenching would work, but studied the process and helped us to teach the metallurgical community how it does indeed work.

Thank you all for enriching my lifelong learning as we are playing in "God's Playground" – metallurgy.

## **Appendix**

### **Five recent examples of integrating optimized three dimensional heat treating processes and equipment for lean manufacturing and part value engineering:**

#### **Case Study 1: Lean Integrated Heat Treating for S-5 Tool Steel Punches.**

The expected failure mode for an S-5 tool steel cold working punch is chipping of the cutting edge after making a certain number of holes. After oil quenching the punch is 60-61 HRC and does not have much ductility. However, after an intensive water quenching the same design punch made of the same S-5 alloy steel tempered to the same 60-61 HRC hardness will punch two to nine times more holes before having to be replaced. The failure mode for the intensively quenched punch is not chipping, but even wear – the punch becomes undersized.

The as-quenched hardness is about the same whether the S-5 punch is oil quenched or water quenched – 62-63 HRC for oil and 63-64 HRC for water, and after tempering the hardness is identical at 61-62 HRC. The reason the same design, made of the same material, hardened punch can offer a much better value proposition ("many more holes") is the compressive residual surface stresses\* created during the "intensive water-then-air quench" (\*as measured by X-ray diffraction). The residual surface stress state for the oil quenched punch is tensile at approximately +200 mPa/29,007 psi tensile. In contrast the residual surface stress state for the intensively water quenched punch is highly compressed at - 900 mPa /130,534 psi compressive. This means that while the oil quenched punch is primed to chip with 29,007 psi of force pushing grains off the cutting surface, the surface grains of the intensively water quenched punch are being held in place with a combination of hoop and axial compressive forces of over 130,000 pounds-force per square inch.

The combination of optimal hardness, ductility and compressive surface stress state make the uniform and intensive water quenched tool punch more holes per punch. Since the customer is "buying holes" (not punches) the punch maker is selling a better value to the end-user and still able to make a higher profit margin.

#### **Case Study 2: Shorter Carburizing Cycles for Case Hardened Parts Made of Low or High Alloy Carburizing Steels with Higher Compressive Residual Surface Stresses for Better Fatigue Life and Damage Resistance.**

The higher the residual compressive surface stresses, the longer the part cyclic fatigue life that can be expected. This is because the surface compression holds the part like a die

and this compressive force must be overcome before the part will begin to bend and then fatigue.

The reason that case hardening of a martensitic steel part imparts surface compressive stresses is the crystalline structure in the martensite shell is Body Centered Tetragonal Iron (BCT). BCT grains have a larger volume than the Face Centered Cubic structure in the austenitized surface layer. The larger volume BCT grains literally press against each other and the contiguous grains in the “case” creating hardness and strength under compression. The martensite not only imparts hardness (strength), but the compressive stresses will also help resist bending fatigue in the hardened layer.

One way to increase surface compression is to case harden the part by heating only the shell of the part (by selective induction or flame heating) to the austenitizing temperature, keeping the core cold, then quenching to produce a martensite shell. Since the core remains soft, there is no martensite phase change swelling to BCT to reduce the compression in the martensite surface layer.

Beneficial surface compressive stresses can also be induced into the surface of the part by mechanical shot peening after hardening.

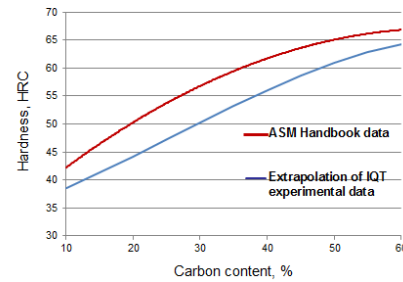
A third way to impart beneficial compressive surface stress is through carburizing the surface, adding carbon atoms to the steel part surface layer then hardening that layer by quenching. During the high temperature carburization process a carbon rich gas atmosphere diffuses carbon atoms in the part surface layer raising the percentage of carbon from the base carbon steel (usually .10% C to .20% C) to .70% C to 1.10% C.

The higher the carbon percentage in the case gradient, the greater the hardenability of the austenite will be when quenched from the austenitizing temperature (~ 1550°F / 843°C). When a case carburized part has between .65% C to 1.10% C diffused in its surface layer and the carbon is diffused into the shell to required case depth, it is ready to be quenched. The additional atoms of carbon also adds volume to the grains creating compression in addition to the higher volume martensite BCT grains.

As shown below, the higher the percentage of carbon, the higher the hardness in the steel as quenched. In addition, the faster the hot austenite is quenched for a given level of carbon diffused into the case, the higher the as quenched hardness in the case at that depth of diffusion (a minimum 50 HRC is usually considered to be the measure of the “Effective Case Depth” (ECD). The oil quench needs approximately .30% C to achieve a minimum level of 50 HRC in the case. The intensive water quench only needs .02% C in the case to achieve 50 HRC minimum for the same ECD. This means that an intensive water quench cooling rate when applied to a carburized part significantly reduces the carburizing cycle times by 30% to 50% compared to a traditional oil quench to achieve a minimum hardness of 50 HRC ECD.

## IQ Process Reduces Carburization Cycle

Correlation Between Steel Hardness And Carbon Content



- For a given carbon content, the IQ process provides greater hardness compared to conventional oil or water quenching processes.
- Effective Case Depth (ECD = 50 HRC) achieved with lower % Carbon in the case gradient.

The physical mass of the carbon atoms diffused into the case also increases the compressive residual surface stresses in the hardened martensitic case. Combined with the austenite to martensite phase change expansion, the added mass of the carbon atoms increases the volume of the crystalline structure that puts the case under higher compression than it would be for a “through-hardened” part of similar carbon content.

As the surface shell quenches and martensite phase change volume expansion occurs, and like layers of an onion, the layers below will also expand. Depending on the thermal gradient and the timing of the formation of layers of martensite on the surface shell, the swelling below the shell will partially or fully cancel the compression formed in the layers above. This phase change expansion below the surface and cancellation of compressive stress in the layers above can be so complete that depending on the timing of the expansion relative to when the shell was formed, in high hardenability steels the core swelling can blow off the hardened surface layer and crack the part.

Therefore, if a part is through-hardened, the initial surface layer of compression (formed as the surface shell cooled to higher volume martensite) can be cancelled as the part layers below cool to the martensite start temperature and begin to swell. So a higher hardenability “better alloy” steel used for either a case hardened part or a through-hardened part can be detrimental to the formation and retention of beneficial compressive surface stresses and reduce cyclic fatigue life. This lower cyclic fatigue life is due to a combination of the higher core hardness that has less ductility and also the reduction of residual compressive stresses that resist the bending fatigue at the surface.

The way to overcome the cancellation of the beneficial surface compressive stresses in the surface shell from the core swelling in high hardenability steels (e.g., 52100) is to form high “current” compressive surface stresses in the martensite surface shell as fast as possible over the hot core while it is still thermally swollen austenite. To create this very high



thermal gradient between the cold martensite surface shell and the thermally swollen austenitic core is to ***uniformly and intensively*** cool the shell. A uniform and intensive cooling rate at the surface very quickly forms the martensite shell and creates high “current” compressive stresses in the surface shell. As the thermally swollen core shrinks, it will draw down the surface shell under even higher compression.

If the intensive water quenching surface cooling rate is then interrupted when the core is still above the martensite start temperature, and the part allowed to finish cooling in the air, the transformation in the core is slowed, and the associated core swelling at martensite start is likewise slowed. The combination of an initial uniform and intensive water quench cooling rate and the interruption at the time of maximum current compressive surface stress will allow the formation of optimal residual compressive surface stresses in even high hardenability, “through-hardening” grades of steel. An added benefit from the uniform and intensive quench is a finer grain structure from a given alloy of steel.

The current compressive stresses in surface shell also hold the part like a die over the hot, still plastic, core. Once this hard and uniform surface shell is formed, it holds the core as it cools by uniform conduction. The uniform cooling of shell and core make the size change more predictable and consistent. Uniformly and intensively quenched gears can actually be machined before heat treat so that they will “distort to fit” after quenching into a near net shape that needs less hard machining or grinding.

The combination of high residual compressive surface stresses, the finer grain from a given alloy of steel, and low, predictable distortion are perfect for longer fatigue life as well as lighter, higher power density parts, that need less post-hardening processing (e.g., hard machining or grinding).

The advent of high quality “limited hardenability” (LH) steels yields this same combination of benefits cited above, but also eliminates the need for the long batch carburization cycle. Ultra-low alloy plain carbon steels with between .60% C to 1.00% C, when through-heated and then uniformly and intensively water quenched, can produce a case hardened surface layer with extremely high residual compressive surface stresses, and a properly toughened core. The elimination of the batch carburization cycle also makes in-line, single-part flow a reality for “case hardened + core toughened” parts. With single-part induction through-heating, automated part handling and uniform and intensive water quenching, the complicated atmosphere generators and controls for the carburization process are also eliminated; further leaning out the manufacture of case hardened parts.

### **Case Study No. 3: Lean Integrated Heat Treating for “Field Reparability”**

The optimal hardened part form, fit and function, may have other indirect requirements that should be considered by the lean manufacturing team, such as using an alloy of steel that has “field reparability” and still provide the needed mechanical properties. For example, the alloy of steel used for a forged gear rack must have all the needed mechanical properties, both surface hardness and core toughness, to function reliably after hardening. In addition, the end-user of a large piece of equipment where the rack is employed must be able to weld a replacement rack on the machine, or repair the gear rack component while the piece of equipment is still in the end-user’s remote location.

A part designer may choose a 4330 alloy material, for its ability to provide the needed mechanical properties in the middle of the part after quenching in oil. However, the 4330 rack cannot be weld repaired, or replaced in the field, without the need to pre-heat or post-heat the weld to prevent the gear rack from cracking.

If the part designer consults the part forger, as well as the part heat treater, the part can be forged from a lower alloy 4130 steel that is then intensively water quenched to obtain the same required hardness, ductility and compressive surface stresses as the more expensive 4330 material quenched in oil. However, the lower alloy 4130 material does not require pre- and post-weld heating, and can be weld repaired or replaced in the field without cracking. In fact the higher residual compressive surface stresses on the part gear teeth (if they were not machined off the rough forging) should extend part fatigue life for the lower alloy 4130 part versus the oil quenched 4330 with its higher hardenability. So the optimal hardening alloy of steel for the intended quench is the less expensive 4130.

### **Case Study No. 4: Lean Integrated Heat Treating for Ductile Iron Castings**

For many years, ductile iron castings have been given improved mechanical properties with austemper heat treat quenching processes in hot salt. Austempered Ductile Iron (ADI) was pioneered by Applied Process by close collaboration with the ductile iron foundries. ADI parts have replaced many steel parts with better mechanical properties, high ductility, low predictable distortion and at a lower overall cost of manufacture. The unique physical properties of ductile iron for noise and vibration dampening, as well as machinability and lubricity from the graphite particles bring additional value added benefits to the lean part manufacturer that collaborates with their ADI heat treater.

More recently, high quality, continuously cast ductile iron (Dura-Bar®) has been the raw material for hardening with an intensive water quenching process. This collaboration of the ductile iron material maker, the part makers, and the heat treater makes for Intensively Quenched Ductile Iron (IQDI®) products that can provide a better “bundle of properties” to the

end-user at a total lower cost than the hardened steel parts they replace.

IQDI parts have a deeper hardened layer to a higher hardness than oil quenched parts. While oil quenched ductile iron parts have undesirable residual tensile surface stresses, the uniformly and intensively water quenched, then air cooled, and tempered, ductile iron parts exhibit beneficial compressive residual surface stress.

The IQDI combination offers a strong and lubricious alternative for D-2 tool steel rolling mill guide rolls, or high alloy ductile cast irons, and since the ductile iron is a dissimilar material to the steel being rolled, there is no product “pick-up” on the rolls. Clay tile forming dies made of IQDI do not spall or chip due to the high compressive residual surface stresses. The lubricity and surface compression of IQDI thread rolling dies can also offer better wearing dies at a total lower cost of manufacture than tool steel dies.

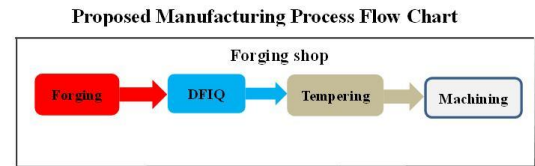
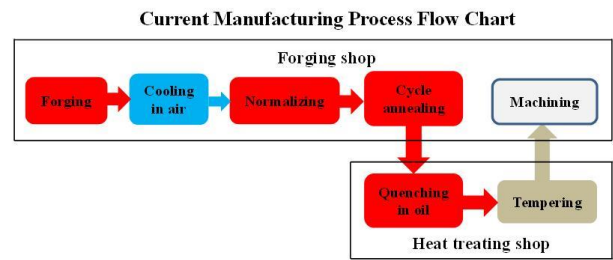
To implement IQDI fully for lean part manufacture, additional material characterizations of the ductile iron material must be done to predict the response to hardening with intensive water quenching.

### Case Study No. 5: Lean Integrated Heat Treating for Direct from the Forge Intensive Quenching (DFIQ).

Lean integrated heat treating solutions cannot be fully implemented without the development of the proper heat treating equipment. With Direct from the Forge Intensive Quenching (DFIQ) equipment on the forging shop floor, the forger is also the part heat treater; the forger becomes a “captive heat treater” adding more value to the forger’s link in the manufacturing chain.

DFIQ processing equipment “uniformly + intensively” water quenches the hot (~ 2,000°F / 1,093°C+) forging as soon as it is removed from the forge or the trim die. The DFIQ forging does not need to be normalized, and does not require a third re-heating to the austenitizing temperature for quench and temper.

After coming directly from the forging trim dies, the hot forging is uniformly and intensively water quenched until the “current” compressive stresses on the part shell are at their maximum value, and then the intensive water quench is interrupted. As the part is then cooled in the air, the hot core “snap tempers” the martensite on the part surface shell. After the “snap temper,” the part is tempered at the required temperature and for the time necessary to develop fully the required as-tempered “hardness and ductility” throughout the forging for the next step in the part manufacture.



**Direct from the Forge IntensiQuench  
(DFIQ<sup>TM</sup>) = Lean 3-D Heat Treating**

Since the forged part is heat treated directly from the forge, the time and expense for transporting the part to and from the heat treat are also saved. This shortens delivery times and also saves energy.

The application of the DFIQ can provide the forging with all the mechanical properties of traditional heat treatments after forging. The combination of DFIQ process and the newly developed water quenchant additives reduce heat treating production costs for forgings by up to 75%. DFIQ is lean heat treating, on the optimal material, integrated into lean part making at its best.

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