
ASM Heat Treating Society Conference
Columbus, Ohio

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+ Akron Steel Treating Company
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A Leaner + Greener Heat Treating Future:

ASM Vision 2020

To Achieve Vision 2020

An R&D Plan for the Heat Treating Community

BACKGROUND AND INDUSTRY NEEDS

Industry needs have been determined from the information brought forth by various committee efforts and surveys over the last five years. Heat treating industry executives identified many of these needs, and prepared a view of the ideal future. This view has been named Vision 2020, and the established performance targets, based in energy, environment, productivity and quality, and industry performance are:

- 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%
- Achieve zero distortion and maximum uniformity in heat treated parts
- Return 25% on assets
- Create 10-year partnerships with customers.
3-D Heat Treating
+ LEAN Part Design = ∅ WASTE

Better parts at a lower cost . . .
“Lean-Integrated Heat Treating” is the controlled application and removal of Heating + Cooling to OPTIMIZE* the crystalline grain structure + the compressive surface stress state of the least costly (Optimal Hardenability) metal alloy to consistently obtain the desired changes while minimizing undesirable changes* in the part.

(* Distortion/size change, non-uniform Hardness + Ductility, etc.)

\[
\text{Hardness} + \text{Strength} \quad \text{Ductility} + \text{Toughness} = (\text{Stress State} + \text{Part Size Change})
\]
Lean Part Making Value Chain: Collaborate + Optimize @ Each Step!

Part Designer
- FEA Model (DANTE)
- Fit + Function + Mechanical Properties
- Consider the Optimal Compressive Stress States (thru All Processing)

Part Manufacturer
- Material Preparation
- Machining + fabrication steps prior to heat treat
- Machining, Grinding after HT
- Minimal or No post-HT processing is the Goal +
- “Near Net Shape Parts”

Material Supplier
- Alloy Cost and Availability
- Wrought, Forged or Cast (IQDI)
- Optimize Mechanical + Physical properties for a given alloy
- Consider the optimal intended Heat Treat Process to Be Used
- DFIQ

Lean Heat Treater
- 3-D Heat Treat Process for Optimal Hardness + Ductility + Stress State* = (Modelled)
- Optimal Grain Refinement for a given Alloy +
- Predictable Distortion (Manageable Size Change)

“Better Parts” for End-User @ Lower Cost

10/20/2017
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Lean-Integrated Heat Treating Quenching Solutions for Uniform Hardness + Predictable Size Change

“Kettering studied the solutions to problems he or others had already solved and reached the conclusion that solutions lie within the problem.

He noticed solutions were merely a change in perception, since the solution to the problem existed all along, within the problem itself.

A problem solver’s role was not to master a problem but to make it generate its solution.

So in your pursuit of simplicity, when you encounter a problem, recognize that your solution likely is right along side the problem itself.”
Five Case Studies Demonstrating Lean-Integrated Heat Treat Benefits:
1. IQ’d S-5 Tool Steel Punches (2 to 9X more holes)
2. Shorter (Complete Elimination) of Batch Carburizing Cycle for Case Hardened + Core Toughened Parts
3. Field Reparable 4130 Gear Racks (not 4330)
4. Intensively Quenched Ductile Iron (IQDI®)
5. Direct from the Forge Intensive Quench Processes (DFIQ™)
Traditional Heat Treat Theory:

“Quench Cooling Rate vs. Probability of Distortion”

Two Types of Quench “Size Change” =
1. Thermal Shrinkage (@Ac3 to Ms) +
2. Phase Change Volume Expansion (@ Ms to Mf Temperatures)
New Heat Treat Specification for Quench Uniformity

- “3.X.A - Parts shall be quenched with the maximum possible severity that can be achieved without quench cracking, to produce the maximum expected as-quenched surface hardness and depth of hardening. A uniform martensitic structure shall be produced on all surfaces, below the MAD, to a depth commensurate with material hardenability and section size. Spotty hardening shall not be permitted and is evidence of insufficient quench flow velocity (Figure 1 gives a schematic of spotty hardening shown by a mixture of light and dark etching at the part surface, and a uniform martensitic structure shown by light etching at the part surface).”

- “3.X.1 Achieving this microstructure specification typically requires an impingement quench flow velocity on the entire surface of a part in excess of 0.76 m/s (2.5 ft/sec) for water and 1.07 m/s (3.5 ft/sec) for oil.”
Integrated 3-D Heat Treat Distortion Control:

**Optimal Steel +**

**“Uniform”**
Gas or Hot Salt Quench
For Uniform Grains

**“Uniform + Intensive”**
Water Quench Controls
Size Change for
Predictable Distortion
Modes of Heat Transfer During Quenching
I. **Film boiling** – a vapor blanket develops on the part surface due to a very high rate of vapor bubbles formation. This is a sporadic and non-controllable mode of heat transfer resulting very often in part excessive distortion.

II. **Nucleate boiling** – vapor bubbles do not merge. This mode of heat transfer is characterized by very high heat extraction rate.

III. **Convection** (no boiling).
“Uniform” + “Intensive” Quench = Consistently *Predictable* Distortion

Intensive water quenching

**Uniform** hardened layer with “current” + “residual” **COMPRESSIVE** stresses holds part together reducing part distortion and eliminates cracking

Conventional oil quenching

**Non-uniform** hardened layer with residual **TENSILE** stresses results in excessive part distortion and possible quench cracking

Ø25x300mm key-way shaft distortion data

<table>
<thead>
<tr>
<th></th>
<th>Batch oil</th>
<th>Single oil</th>
<th>Single IQ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ø25-0.51mm</td>
<td>0.25-0.51mm</td>
<td>0.20-0.36mm</td>
<td>0.08-0.12mm</td>
</tr>
</tbody>
</table>
Improvement of Microstructure for Through-Hardened Steels

Core microstructure for Ø27mm rod made of 43XX steel after IQ and oil quenching (data provided by Benet Labs)

Martensite structure was obtained for both rods. Micrographs clearly indicate significant grain refinement* and smaller grains from the IQ process versus traditional oil quenching.
Thermal + Grain Phase Changes
Distortion = Part Cracking
“Lean-Integrated Heat Treating” is the controlled application and removal of Heating + Cooling Cycles to OPTIMIZE* the crystalline grain structure + the compressive surface stress state of the least costly, Optimal Hardening, metal alloy to **consistently** obtain the desired changes, while **minimizing undesirable changes*** in the part.

(* Distortion/size change, non-uniform Hardness + Ductility, etc.)

**Hardness + Strength**

= **Ductility + Toughness**

= (Stress State + Part Size Change)

 Balanced Part Properties
Optimized Hardness + Ductility + Compressive Surface Stresses = Better Mechanical Properties from the OHIQ Material + Longer Part Service Life = LEAN TOTAL LOWER COST OF MFG.
Three Types of Grain Size Change In Heat Treating (AKA Distortion)

1. Thermal Expansion (Heating) + Shrinking (Quench Cooling)

2. Phase Change Expansion on Austenite (FCC) to Martensite (BCT) Grain Transformations

3. “Latent size change” stress state changes from retained austenite to untempered martensite phase changes over time
Iron-Carbon Phase Diagram

Austenitizing Temperatures -vs- % Carbon

TEMPERATURE

°C  °F
1100  2000
1000  1900
900   1800
800   1700
700   1600
600   1500
500   1400
400   1300
300   1200
200   1100
100   1000

PERCENT CARBON

0.1  0.2  0.3  0.4  0.5  0.6  0.7  0.8  0.9  1.0  1.1  1.2  1.3  1.4  1.5  1.6  1.7  1.8  1.9  2.0

UPPER TRANSFORMATION TEMPERATURE LINE
LOWER TRANSFORMATION TEMPERATURE LINE
TTT Diagrams: The Road Map for Hardening

Carbon Steels: 0.35C

Chromium-Molybdenum Steels: 4130

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“TTT Fractals” for Each 1035 “Grain”

- TTT Diagram shows the proper cooling rate to obtain martensitic structure.
- For low distortion AND uniform hardness, you must cool all the grains within the boundaries set forth by the alloy’s TTT diagram.
- Uniform cooling on the surface translates into uniform cooling of the subsurface cells.
- NO Boiling = Uniform Cooling
Direct Convection Cooling – NO Boiling
Dynamics of Temperature, Structural and Stress Conditions (by DANTE modeling)

Ø25mm cylinder made of AISI 1045 steel (Ms=320°C)

Intensive quenching

Surface stresses, \( \sigma \)

-1,000Mpa

T \( = 0 \) seconds

A

835°C

IQ

Oil quenching

T <0.2 seconds

T = 18 seconds

A

835°C

Oil quenching

A

400°C

Start of martensite formation

Final steel microstructure

M

>50%M

Oil quenching

B

-200Mpa

+\( \sigma \)

Surface stresses, \( \sigma \)
Lean + Green Integrated in 3-D Heat Treating Optimal Grains + Compressive Surface Stress State + Predictable Size Change

OHIQ Steel Alloy
± Predictable Distortion

“Uniform”
Gas or Hot Salt Quench
or
“Uniform + Intensive”
+ OHIQ Steel Alloy + Optimal Surface Shell or Uniform Through-Heating
or
Optimal DAT Through-Heating

“Hardenability” of Quench + DISTORTION

Quench Cooling Rate

Air Hot Salt Oil Water

Optimal Grains + Compressive Surface Stress State + Predictable Size Change
Martemper or Austemper Process with Molten Salt Quenching on Small + Thin Parts Uniform Thermal + Grain Phase Changes (NO Boiling)
IQ process provides greater hardness for the same carbon content in the case carburized layer compared to oil quenching, resulting in a deeper ECD for the same carburizing cycle.
New CNC machining techniques + standard carbide tooling allow holes and slots in 59 HRC part without heating part – heat goes into chip . . . No change to mechanical properties.
## Shock Resisting S5 Steel Punches

**Steel chemistry:** C-0.55; Mn-0.8; Si-2.0; Mo-0.4

### Compressive Stresses at Work:
**Punch mechanical properties**

<table>
<thead>
<tr>
<th>Property</th>
<th>Oil Quench</th>
<th>Intensive Quench</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardness, RC</td>
<td>As-quenched</td>
<td>62-63</td>
</tr>
<tr>
<td></td>
<td>As-tempered</td>
<td>60-61</td>
</tr>
<tr>
<td>Impact</td>
<td>@20°C</td>
<td>1.0</td>
</tr>
<tr>
<td>strength, ft·lb</td>
<td>@100°C</td>
<td>2.5</td>
</tr>
<tr>
<td>Residual surface stresses, MPa (PSI)</td>
<td>200 (29,007)</td>
<td>-900 (-130,534)</td>
</tr>
</tbody>
</table>

*Study conducted by Case Western Reserve University of Cleveland, Ohio*
S-5 Punches Intensively Quenched
In “Batch” IntensiQuench System

“Barrel” shape is due to residual surface tensile stresses.

“Concave” shape is due to residual surface compressive stresses.
Compressive Surface Stresses = Punch Lasts Longer

Hoop stresses

Axial stresses

Life = 2X to 9X holes
Intensively quenched punches make up to 9 times more holes compared to oil quenched punches due to high residual surface compressive stresses and improved material mechanical properties. Punch failure mode changed from chipping/spalling to wearing.
Intensively Quenched Ductile Iron

IQDI® Products vs. ADI

**IQDI** = “Carbide Hard” Martensite Structure
Under Residual Compressive Surface Stress
for added Toughness

* Versus *

*Austempered Ductile Iron (ADI)* = Softer Bainite Structure
Under Neutral Stress State

Continuously Cast Ductile Iron has consistently high quality + is less expensive than D-2 Tool Steels +

Lubricity of Graphite Particles = Self-lubricating parts

+ Allows part to be machined 3X faster than 1045 steel
Deeper Hardness Depth: IQDI* vs. Oil Quench

Hardness profile for Ø76x305mm test sample

* Hardness Results from Batch IntensiQuench System
Grain Refinement: IQDI vs. Oil Quench

IQ surface X100

Oil surface X100

IQ core X100

Oil core X100
Stress State:
IQDI (Compressive) vs. Oil (Tensile)
Lubricity: IQDI vs. D-2 Tool Steel
Field Tested IQDI Products

HPIQ + IQDI = Machinable Carbide tooling?
Integrated Heating + Single-Part IntensiQuench® System =

1. “Distort to Fit” A/Q Parts ~ 50 microns average “predictable” distortion  
   (Less grinding + straightening)
2. Shortening of Carburization Cycle by 33% to 50% (less energy use)
3. Low cost water based quenchant + No oil quenchant hazards + cleaner parts
4. Allows use of less costly alloy steels yield needed mechanical properties  
   (OHIQ Materials)
Direct from the Forge IntensiQuench (DFIQ) Unit (Patent Pending, 2017)
Direct from the Forge IntensiQuench (DFIQ™) = Lean 3-D HT

**Current Manufacturing Process Flow Chart**

Forging shop

- Forging → Cooling in air → Normalizing → Cycle annealing → Machining
- Quenching in oil → Tempering → Heat treating shop

**Proposed Manufacturing Process Flow Chart**

Forging shop

- Forging → DFIQ → Tempering → Machining
Key

Pintle adapter

Tine

Lug

DFIQ Test Parts (2017)
Proven IntensiQuench® Applications

1. Automotive parts.
2. Heavy trucks and off-highway vehicles.
3. Aerospace parts.
4. Mining equipment.
5. Steel mill rolls (IQDI)
6. Railroad equipment.
7. Agricultural equipment.
8. Weapon systems.
10. Industrial gears
Commercialized Parts - IQ Batch Process

**S5 steel punches**

Intensively quenched punches make 2 to 9 times more holes compared to oil quenched S-5 tool steel punches.

**1040 steel shafts Ø2 x 26”**

Shaft distortion reduced by 3 times.

**1045 steel forged rings of 9.5"OD**

Quality defects due to excessive ring distortion reduced from 18% to 1%.

**Ductile iron steel mill rolls**

Service life of IQDI® (Ductile Iron) rolls is more than two times longer than rolls quenched in oil; equal to the service life of rolls made of more expensive D-2 alloy tool steel.

**Gear rack**

Lower cost 4130 steel + IQ = performance of 4330 steel + “Field Reparability”
Integrated Heat Treating Solutions
Both “Traditional” + “Advanced” Methods
full collaboration with
Part Designers + End-Users +
Material Makers (OHIQ Alloy Selection) +
All the Members of the Lean Part Manufaturing Team
For more about different IQ Equipment . . .

ASTM International’s
“Intensive Quenching Systems: Engineering and Design”
by N.I. Kobasko, M.A. Aronov, J.A. Powell and G.E. Totten

For more about different IQ Process Methods . . .

ASM Handbook Series *
“Steel Heat Treating Fundamentals and Processes”
by N.I. Kobasko, M.A. Aronov, J.A. Powell and G.E. Totten

Chapter on “Intensive Water Quenching of Steel”
with IntensiQuench® Theory, Practice, Methods + Equipment