Induction Hardening of Gears & Sprockets

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Overview

• Specifics and methods of induction gear hardening
• Single-shot aka Spin hardening
  ▪ Single Frequency hardening
  ▪ Dual Frequency hardening
  ▪ Simultaneous Dual Frequency hardening
• Tooth Scan hardening (Delapena process)
• Tooth-by-Tooth simultaneous hardening
• Computer simulation
• Conclusions
Induction Gear Hardening

Optimal case pattern is a continuously hardened layer on the whole surface:

CONTOUR (PROFILE) HARDENING

Gear tooth loading patterns

Source: Inductoheat
How to Achieve Contour Hardening with Induction Hardening?

1. Austenization by induction heating and quenching of required surface layer

2. Hardening after thermochemical surface treatment (carburizing, etc.)

3. Use of steels with limited hardenability

In cases 2,3 the whole gear or tooth area may be heated to austenization temperature and quenched
Methods of Induction Gear Hardening

Contour Hardening:
1. Single-shot heating at “optimal” frequency
2. Dual frequency heating
3. Simultaneous Dual Frequency (SDF) heating

Local Hardening:
1. Flank heating
2. Simultaneous tooth-by-tooth hardening
3. Tooth-by-tooth scan hardening (Delapena process)
4. Others
Induction heating intensity and heat distribution depends on properties of heated material. For a significant part of the heating process (up to 50%) the surface temperature is above Curie temperature, i.e. the surface layer is non-magnetic.
Main Principle of Induction Heating

Chain of phenomena:

1. Power supply delivers current (I1) to induction coil
2. Coil currents (ampere-turns) generate magnetic field. Lines of field always go around the coil turns
3. Alternating magnetic field flowing through the part cross-section (coupled to the part) induces voltage in the part
4. Induced voltage creates eddy currents (I2) in the part
5. Eddy currents generate heat in the part
6. In each induction system there are at least 3 closed loops: 1. Induction coil; 2. Eddy current loop in the part; 3. Magnetic flux loop
Skin-Effect in Induction Heating

Induced current tends to take the shortest path under the coil turns but it does not penetrate into the metal to a depth \( >1.5 \delta \), where \( \delta \) is a skin or reference depth. \( \delta \) depends upon material properties and frequency. For hot steel (non-magnetic state) \( \delta = \frac{500}{\sqrt{f}}, \text{ mm} = \frac{20}{\sqrt{f}}, \text{ in.} \)

<table>
<thead>
<tr>
<th>F, kHz</th>
<th>10</th>
<th>20</th>
<th>50</th>
<th>100</th>
<th>200</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \delta, \text{ mm} )</td>
<td>5</td>
<td>3.5</td>
<td>2.2</td>
<td>1.6</td>
<td>1.1</td>
</tr>
<tr>
<td>( \delta, \text{ mil} )</td>
<td>200</td>
<td>140</td>
<td>87</td>
<td>63</td>
<td>43</td>
</tr>
</tbody>
</table>

**Example:** spur gear \( M = 4 \text{ mm} \), i.e. \( p = 0.49'' \) and tooth thickness \( s = 245 \text{ mil} \)

To heat tooth **well**, \( \delta \) must be less than \( s/2 \), i.e. \( \delta_{\text{max}} = 122 \text{ mil} \) and min frequency is 27 kHz
Eddy Current Flow Path in Gear

HF current flows along the gear contour

LF current “cuts” the teeth and the gear roots are much more intensively heated

At temperature below Curie point (material is magnetic) skin effect is high even at “low” frequency and current path is similar to HF case
Heat Delivery Requirements

1. Appr. 3 times more heat must be delivered to the root area than to tooth in order to have the same temperature

2. Power density must be high and heating time “short” to avoid temperature equalization in the tooth and thru hardening

3. Smaller the module (or circular pitch), shorter time and higher specific power required
Parameters of Induction Gear Hardening Process

Major parameters of the process: Frequency $f$, Power $P$ and heating Time $t$. Process is dynamic and only a combination of these parameters plus optimal induction coil design can give good results.
Frequency Selection

Power distribution pattern:
Top – Low Frequency
Bottom – High Frequency

Hardened layer pattern:
1 – Low Frequency
2 – High Frequency
3 – Optimal Frequency, Power and Time

Source: Ajax Tocco Magnethermic
Single-Shot Hardening
aka
Spin Hardening
Optimal Frequency for Single-shot Contour Hardening

**Metric system:**
Fopt = K/M², kHz
with M – gear module in mm
K = 350-600 depending on gear tooth geometry, case depth and material

**British system:**
Fopt = (6-10)/p², kHz
with p – circular pitch in inches

Relation: M = 25.4 p/π = 8.085p
with p in inches and M in mm
# Process Parameters

Process is characterized by combination of frequency F, specific power $P_0$ and heating time t. $P_0$ and F can vary during the process.

Total power $P_p = S_p * P_0$ with $S_p$ - heated surface.

<table>
<thead>
<tr>
<th>Module, mm</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circ. Pitch, in</td>
<td>0.37</td>
<td>0.49</td>
<td>0.62</td>
<td>0.75</td>
</tr>
<tr>
<td>$F_{opt}$, kHz</td>
<td>40-65</td>
<td>20-30</td>
<td>10-17</td>
<td>7-12</td>
</tr>
<tr>
<td>Time, sec</td>
<td>0.2-0.25</td>
<td>0.6-0.7</td>
<td>0.9-1.1</td>
<td>1.2-1.4</td>
</tr>
<tr>
<td>Specific power, kW/sq.in</td>
<td>20-24</td>
<td>14-16</td>
<td>12-14</td>
<td>7.5-8.5</td>
</tr>
</tbody>
</table>

This table gives you only estimate values; they must be corrected for a particular gear.
Induction Hardening Pattern

Good contour hardening pattern

Non-uniform contour hardening due to longer than optimal heating at relatively high frequency

Through hardening of the whole teeth area due to too long heating

Source: www.gearsolutions.com
Example of Gear Optimally Hardened by Single-shot Process

Optimal induction hardening provides:

• High surface hardness and contact strength
• High wear resistance
• Favorable distribution of compressive stresses
• High bending strength
• Slow progression rate of pitting

A 6150 spur gear profile hardened using single-frequency single-shot technique

Source: Inductoheat
Gear Contour Hardening

Gear heating: optimal combination of frequency, power and time
Slight overheating of root end areas (may be attributed to the coil design)

Source: www.denkikogyo.co.jp
Heating for Less Than 2 Seconds

Source: Ajax Tocco Magnethermic
Case Hardening of ID Gear Surface

Source: Ajax Tocco Magnethermic
Machined Coil with Integral Quench

Magnetic flux concentrators are highly recommended for ID coils. They dramatically reduce coil current demand, improve process efficiency and part quality.

ID coil with Fluxtrol Soft Magnetic Composite core (concentrator)
Dual Frequency Hardening

Dual frequency hardening is more flexible and reliable process than single-frequency one.
Two Types of Dual Frequency Heating

Dual frequency heating with part transportation

Simultaneous Dual Frequency (SDF) heating. Typical frequencies: 10 kHz and 100 - 200 kHz
Dual Frequency Hardening

Dual frequency hardening may be made by sequential heating at Low and High frequency in two inductors or in the same inductor.

LF heating brings teeth to a temperature slightly higher than Curie point and the roots - to temperature close to a final value.

HF heating must be short. It forms a required austenitized layer on the whole gear circumference.
Simultaneous Dual Frequency Hardening

SDF hardened bevel gear:
Heating time 0.2 sec
Frequencies 10 kHz and 230 kHz
Total power 580 kW

1000 kW SDF machine, Eldec Induction

Source: Book of A. Muehlbauer “History of Induction…”
New Generation of SDF Induction Machines

Total power of SDF machines is up to 3000 kW

The MIND—Modular INDuction—machine.

Source: Eldec Induction
Scanning: Delapena Process
Delapena Style Coil

Inductor and Current Flow Print

Used inductor for large gear hardening

Source: Book of A. Muehlbauer “History of Induction Heating and Melting, Vulkan, 2008”

Source: VNIITVCh, Russia
Coil Positioning with Contact Guide

Difficulties:
- Small gaps “coil-gear” and accurate positioning are required
- Overheating of flanks and underheating of root bottom near the end of gear may occur
- Water sprays required for correction of heat pattern on the tooth tips and at the end of gear.

Source: Ajax Tocco Magnethermic
Flank Sprays Prevent Temper Back on Adjacent Tooth
Double Coil of Delapena Style

This coil allows better temperature control at the beginning and the end of scanning path

Source: www.thermalprocessing.com
Installation for Tooth by Tooth Scan Hardening

Source: Ajax Tocco Magnethermic
Scan Hardening of Large Gear

Gear OD = 750 mm (29.5”)

Weight M = 0.75 t

Teeth number N = 7

Source: VNIITVCh, Russia
Other Methods
Flank Hardening

1 – coil turn; 2 – magnetic controller

Hardness pattern
1,2 – active coil turns; 3,4 – magnetic controllers; 5 – cooling shower; 6 – return coil legs

Example: hardening of tractor satellite gear M = 6.5 mm; process is sensitive to design and setup

Design: VNIITVCh, Russia, 1966
Large Sprocket Hardening

Coil with magnetic controller

Source: VNIITVCh, Russia
Large Gear and Slewing Rings
Hardening

GH Induction machine for large wind generator gear hardening using “tooth-by-tooth” technology
Using Steels with Controlled Hardenability
Gears from Steels with Controlled Hardenability

Technology was developed by Prof. Konstantin Shepelyakovskiy in 1960s, Moscow Automotive plant “ZIL”. It is used in automotive and rail road industries for gears and other components in Russia and Belorussia.
Microstructure of Hardened Gears

Truck gear:
M = 6 mm or
p = 0.74”
DP = 4.2

Miscellaneous Gears:
1 – martensite
2 – sorbite
3 - initial structure

Sorbite X 500
Special Features of the Method

- Low alloyed steels made according to a special technology
- Deep induction or even furnace heating may be used
- Very intensive water quenching is required to achieve optimal results
- Sorbite layer formation under the martensite layer improves gear performance
- Method is low sensitive to heating process

Source: Prof. K. Shepelyakovskiy
Computer Simulation
Simulation of Gear Hardening

Computer simulation of induction gear hardening is one of the most difficult tasks of induction heating due to:

- 3D nature geometry of the system
- Strong coupling of Electromagnetic and Thermal phenomena
- High frequency and large gradients of magnetic and thermal fields require fine meshing
- Frequency variation or application of two different frequencies (in the case of SDF heating)
- System geometry variation in the case of scan hardening (at the extremities of the gear)

In spite of these difficulties at present time we have successful examples of computer simulation of Electromagnetic, Thermal and Structural phenomena and even Stress and Distortion distributions.
3D Simulation of Power Density Distribution in Gear

Source: Ajax Tocco Magnethermic
Current Density Distribution in Gear Tooth

Sketch of gear heating in a single-turn inductor

3D simulation of ¼ of gear tooth; program Flux3D

Source: Ajax Tocco Magnethermic

Source: Fluxtrol. Inc.
Simulation of Dual Frequency Hardening of Worm Gear

Right – simulated temperature distribution (ETP, Hanover)
Left – experimental sample (Eldec Induction)
Conclusions

Advantages:
• Fast processing with individual control
• Carbon and low alloyed steels may be used
• Favorable stress distribution may be created
• Low distortion due to local heating
• Big energy savings
• Environment friendly process
• Possibility of in-line processing
• Very large parts may be treated

Disadvantages:
• Process must be individually developed for each type
• Difficult to harden complicated gear types
“I have been amazed at the testing results of the components that have broken many of the established rules of structure, carbon level, hardness, etc., of the component attributes” – Dick Collins, Borg Warner Automotive, talking about induction hardened parts